CME Focus Studies

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The CME is a beautiful piece of physics

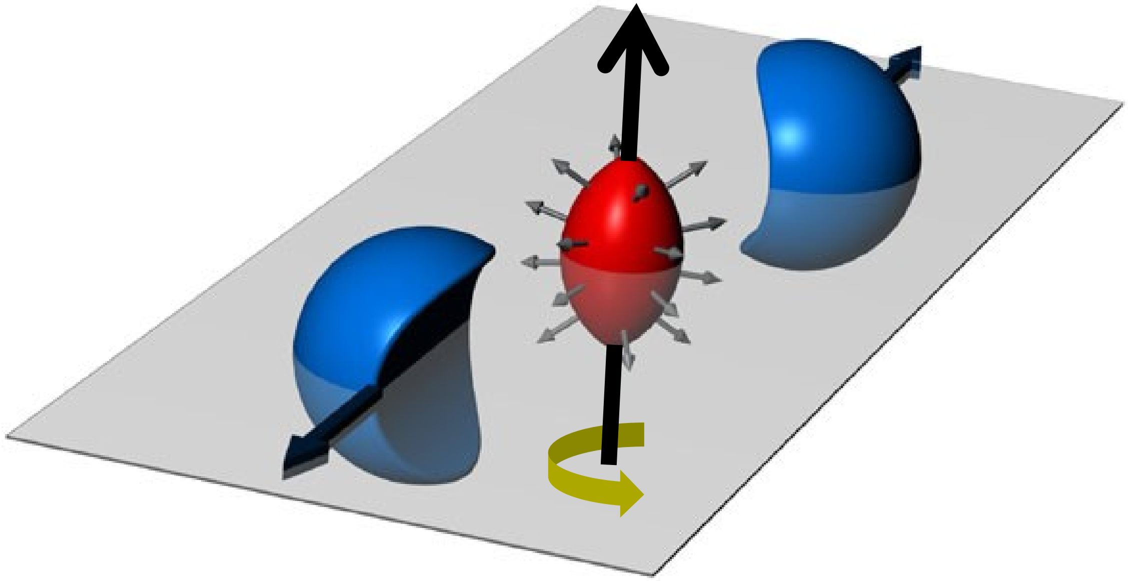
- Theoretical foundations pioneered ~25 years ago
  - Kharzeev & friends, including Volker Koch @ LBL

- The CME requires 3 things that are likely to occur in HI collisions
  - A strong magnetic field (stronger than on the surface of a neutron star)
  - Fluctuating topological charge in dense gluonic fields
  - Chiral symmetry restoration

- These phenomena have robust theoretical foundations but none are individually associated with an experimental observable
  - So, while there is little doubt that these phenomena occur independently, the question is do they occur simultaneously and do they develop a CME signal in heavy-ion collisions with sufficient magnitude to be observed'

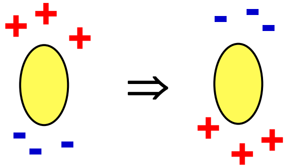
- Today's focus is upon the observable used to find the CME

CME: Separation of Charge with respect to the reaction plane

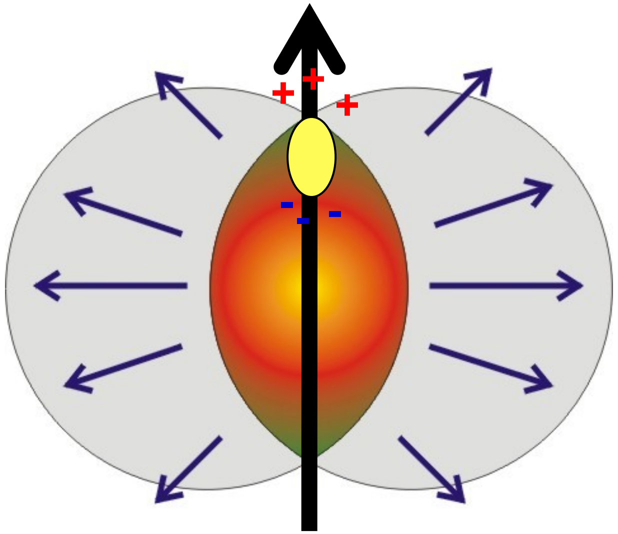


- If a chirally restored bubble is created in a heavy ion collision, the positively charged quarks will go up … then hadronize … and yield an excess of positive pions above the plane
- Unfortunately, it could be just the opposite in the next event depending on the topological charge in the bubble

- The signal is manifestly odd
  $x \Rightarrow -x$, $p \Rightarrow -p$
  but the observable will be even



- The charge-flow asymmetry is too small to be seen in a single event but may be observable with correlation techniques



Full Fourier Transform of the Invariant Yield

$$f(\phi) = \frac{b_0'}{2} + \sum_{n=1}^{\infty} \left(a_n' \sin(n\phi) + b_n' \cos(n\phi) \right)$$

where

$$a_n' = \frac{1}{\pi} \int_{-\pi}^{\pi} f(\phi) \sin(n\phi)\, d\phi \quad \text{for} \quad n = 1, 2, \ldots$$

$$b_n' = \frac{1}{\pi} \int_{-\pi}^{\pi} f(\phi) \cos(n\phi)\, d\phi \quad \text{for} \quad n = 0, 1, 2, \ldots$$

If we want to test if parity is conserved then we should keep the extra terms

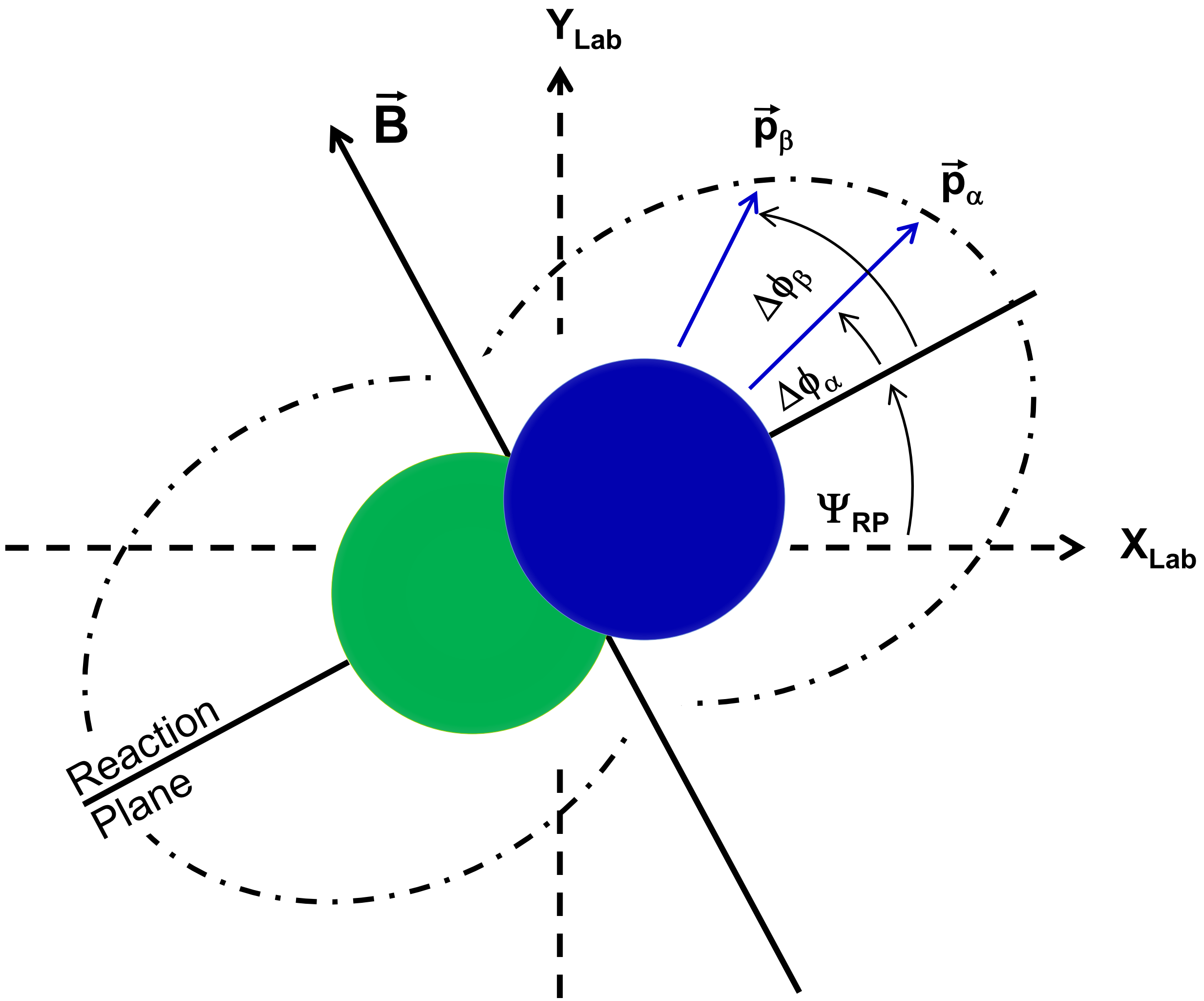
$$E \frac{dN^3}{d^3p} = \frac{1}{2\pi} \frac{d^2N}{p_T dp_T dy} \left(1 + \underline{2a_1 \sin(\Delta\phi)} + 2b_1 \cos(\Delta\phi) + \underline{2a_2 \sin(2\Delta\phi)} + 2b_2 \cos(2\Delta\phi) + \ldots \right)$$

where

$$a_n = \pi\, a_n' = \sum_i \sin(n(\phi_i - \Psi_R)), \qquad b_n = \pi\, b_n' = \sum_i \cos(n(\phi_i - \Psi_R))$$

The standard HI flow analysis assumes a = 0 and assigns $b_n \equiv v_n$

Analysis Uses Standard Flow Tools

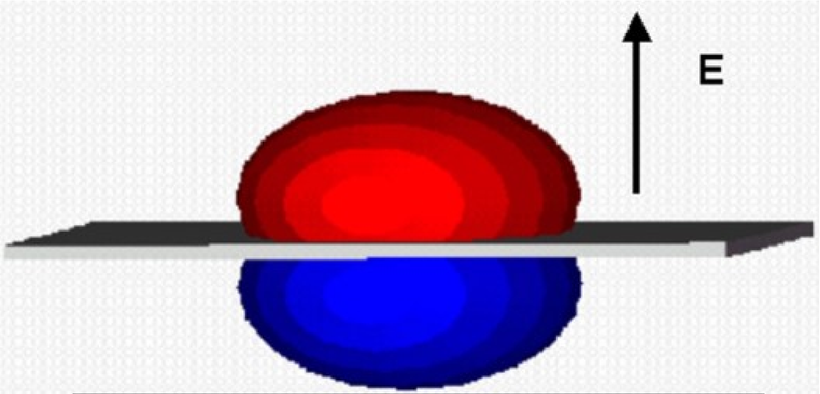


- The line between the centers of the nuclei and the beam axis define the reaction plane – perpendicular to angular momentum vector and B field

The observable and the tools for analysis

n=1: Directed Flow has a period of 2π (only one maximum)

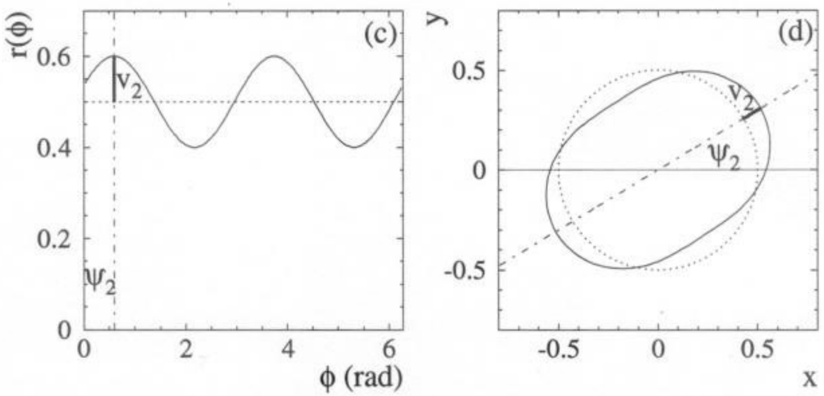
– v_1 measures whether the flow goes to the left or right – whether the momentum goes with or against a billiard ball like bounce. For collisions of identical nuclei, symmetry forces v_1 to be an odd function of η



Treat CME as a form of Directed Flow

n=2: Elliptic flow has a period of π (two maximums)

– v_2 represents the elliptical shape of the momentum distribution. It is an even function of η for identical nuclei



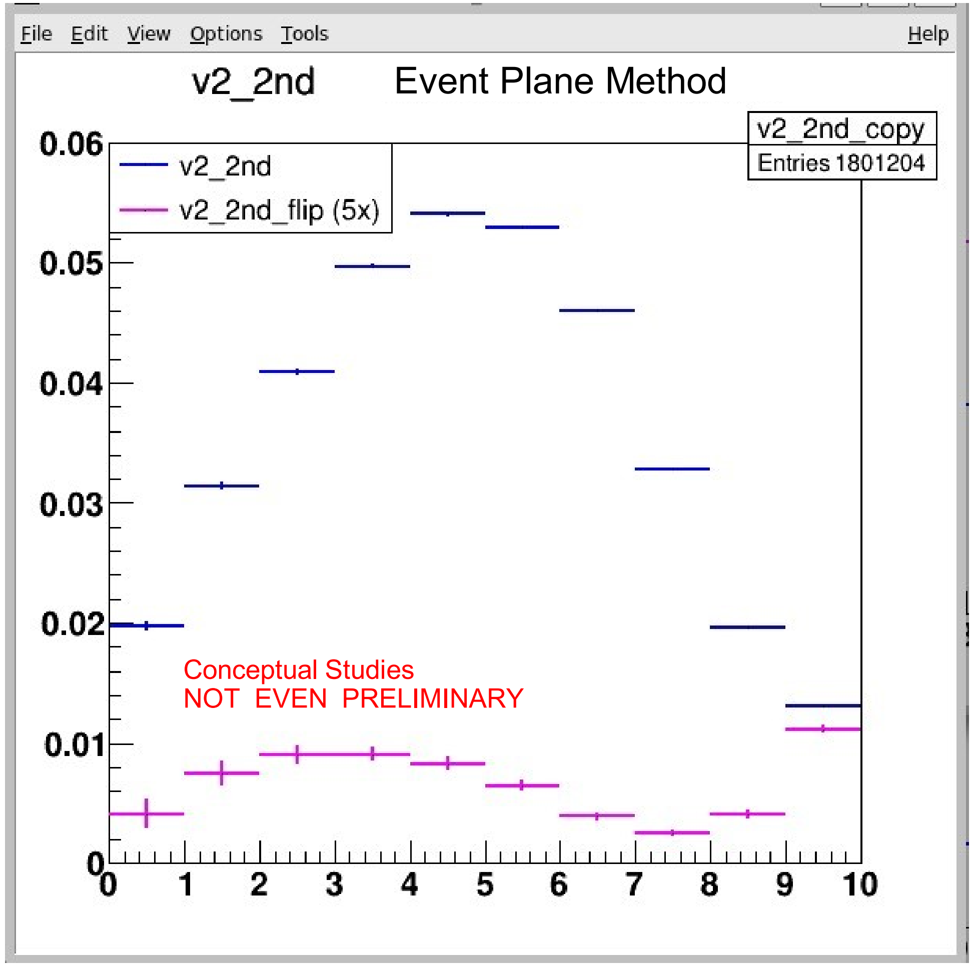
Perform a Fourier Transform to isolate the coefficients

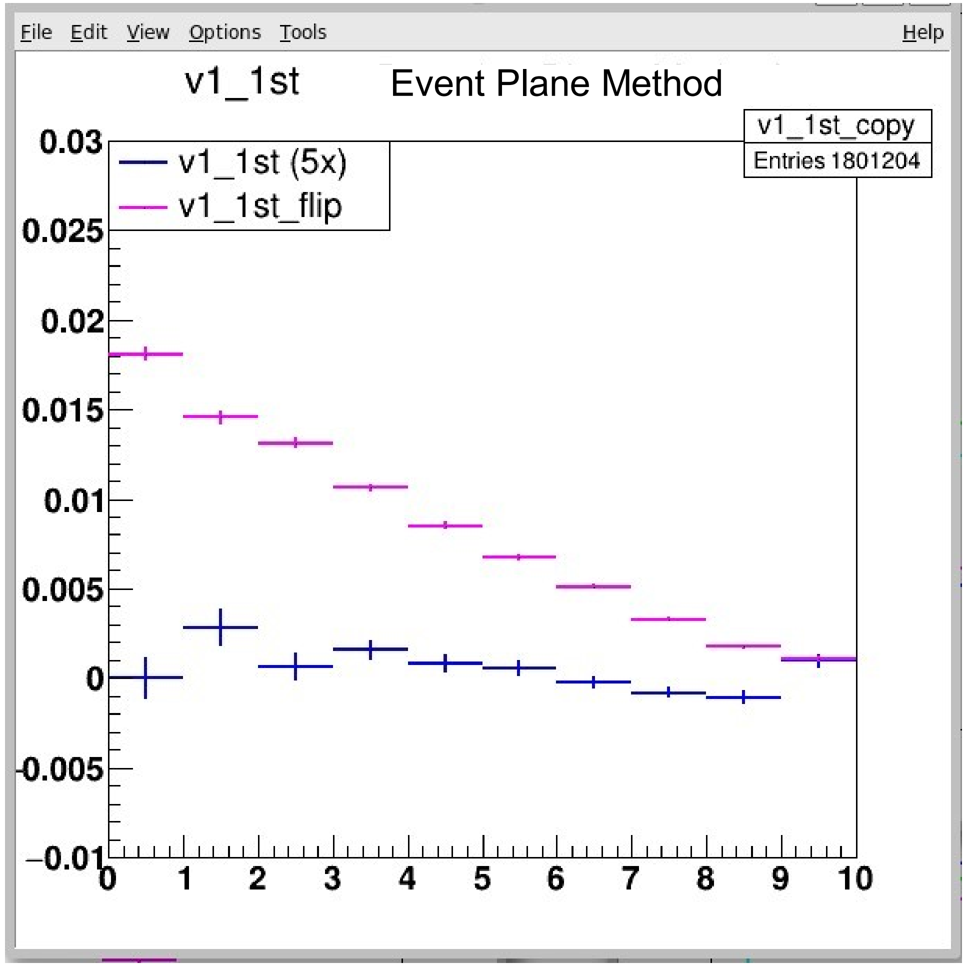
sin() terms may be non-zero if parity isn't conserved

$$E\frac{dN^3}{d^3p} = \frac{1}{2\pi}\frac{d^2N}{p_T dp_T dy}\left(1 + 2a_1\sin(\Delta\varphi) + 2v_1\cos(\Delta\varphi) + 2a_2\sin(2\Delta\varphi) + 2v_2\cos(2\Delta\varphi) + 2v_4\cos(4\Delta\varphi) + \ldots\right)$$

isotropic (1), **parity non-conserving** ($2a_1\sin(\Delta\varphi)$), **directed** ($2v_1\cos(\Delta\varphi)$), **h.o. nc terms** ($2a_2\sin(2\Delta\varphi)$), **elliptic** ($2v_2\cos(2\Delta\varphi)$), **higher order terms** ($2v_4\cos(4\Delta\varphi)$)

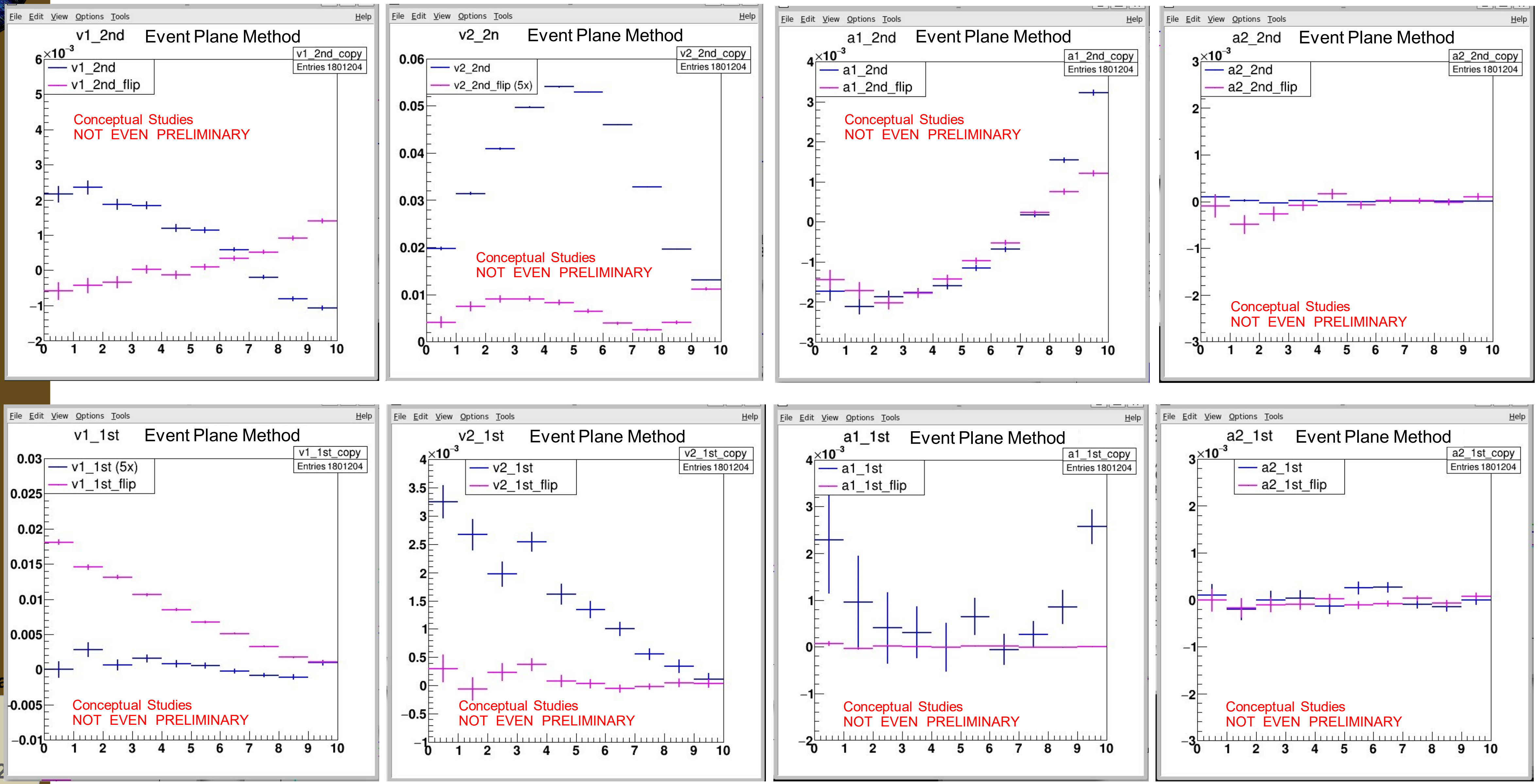
v_1 and v_2 in Au-Au 200 GeV (~1 Million events from Run 19)





v_1 and v_2 doing familiar things (Note: Ψ_1 & Ψ_2 EPs measured in TPC)

Several more low order terms …



The γ observable

- The coefficients of the Fourier expansion for the invariant yield are

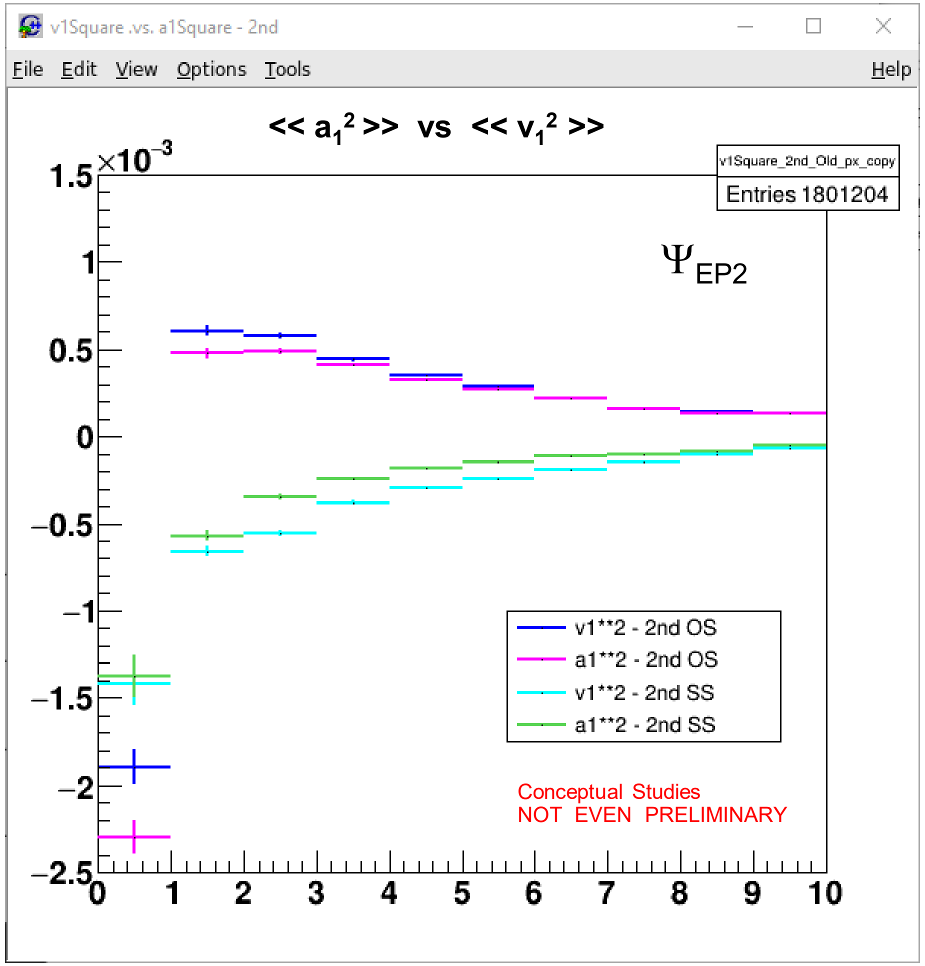
$$v_n \equiv \langle \cos(n(\varphi - \Psi_R)) \rangle \qquad \text{or} \qquad v_n^2 = \langle \cos(n(\varphi_i - \varphi_j)) \rangle$$

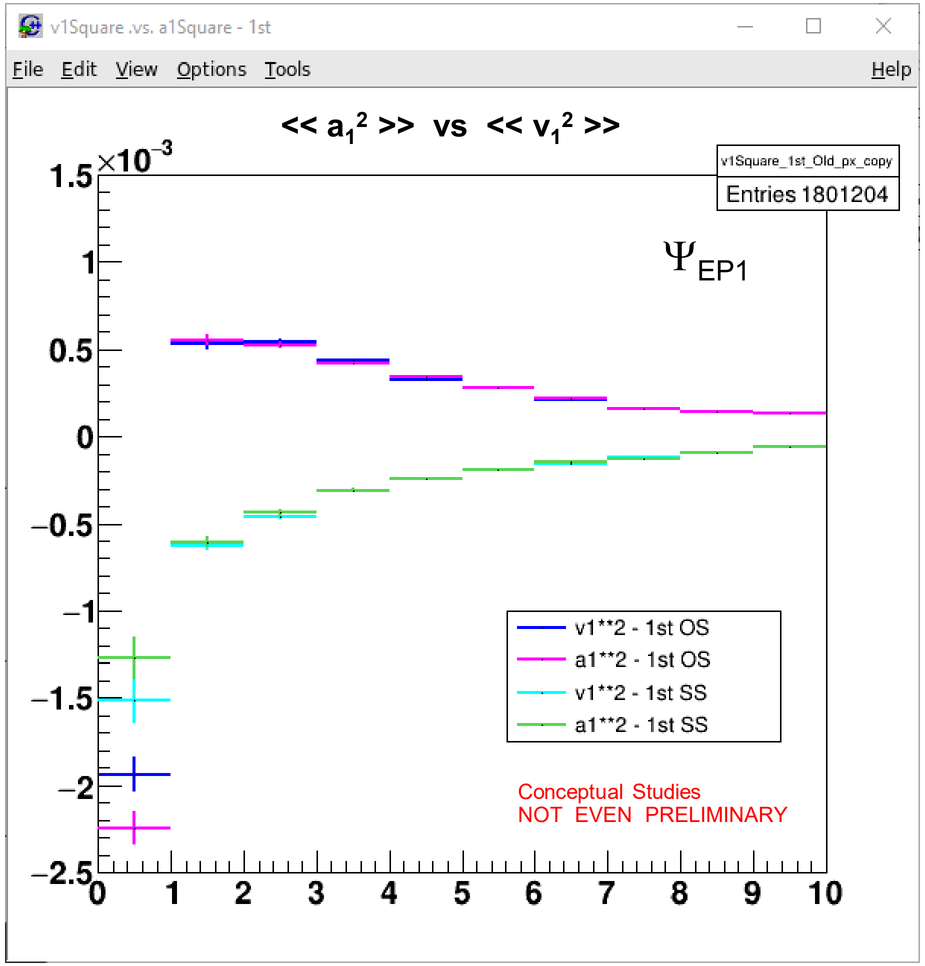
  - where the average is taken over all particles in the event and ψ_R is the known event plane angle (e.g. from the TPC or the EPD)
  - The equation on the right is a multi particle correlation
- Under certain assumptions v_1 is directed flow
  - Note that 'normal' v_1 measurements in a symmetric Au-Au collision have an intrinsic symmetry that requires weighting by sign(η) to measure $v_{1\ Hydro}$
  - Tool: look for charge flow (up/down) without sign(η) weighting because $v_{1\ Hydro}$ will cancel out if we have symmetric η acceptance.
- γ is a clever observable. A triple correlation $\Rightarrow \langle \cos(\phi_i + \phi_j - 2\phi_k) \rangle$
  - Mixed Harmonics: $\langle \cos(\varphi_i - \varphi_k)\cos(\varphi_j - \varphi_k) - \sin(\varphi_i - \varphi_k)\sin(\varphi_j - \varphi_k) \rangle = (v_1^2 - a_1^2)\, v_2 + \ldots$
  - A good candidate to measure charge sensitive flow since $v_1 \Rightarrow 0$ and hopefully v_{1_bkgd} (~in-plane bkgd) cancels a_{1_bkgd} (~out of plane bkgd), thus:

$$(v_1^2 - a_1^2) * v_2 \Rightarrow -a_1^2 * v_2$$

  - Should work well when v_1 is small and v_2 is large

a_1^2 and v_1^2 from the 200 GeV Au-Au Run 19

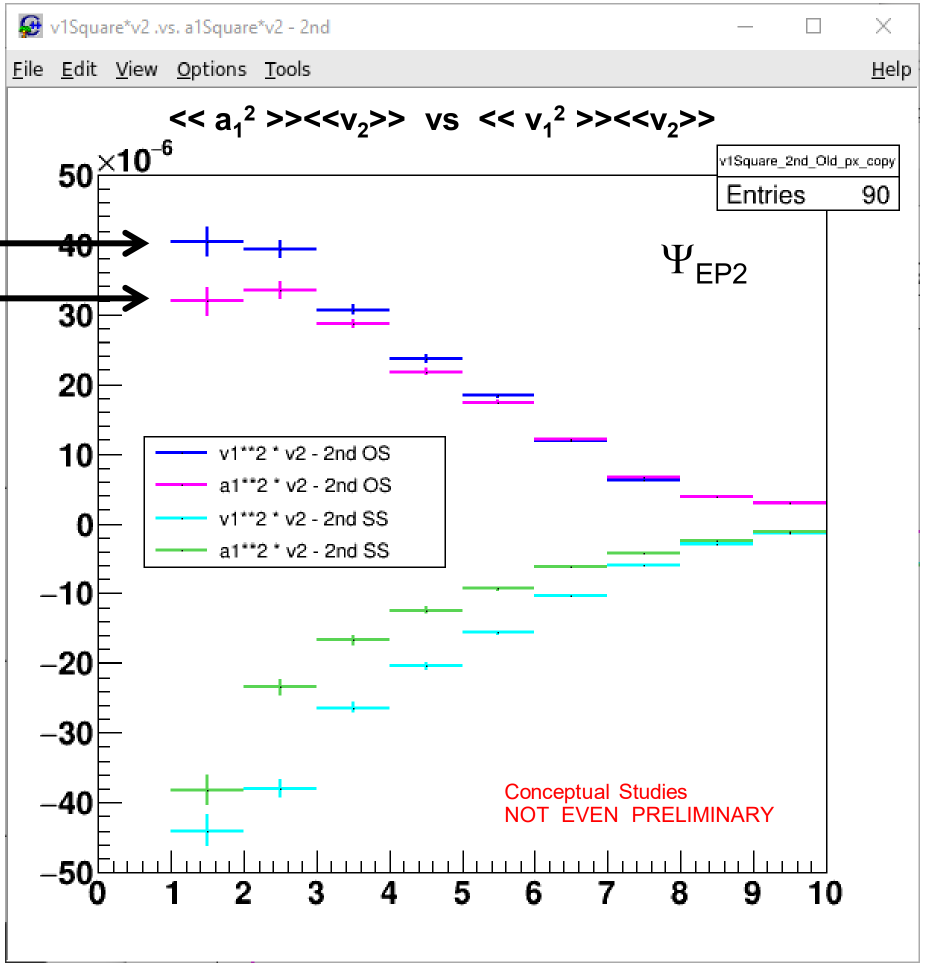


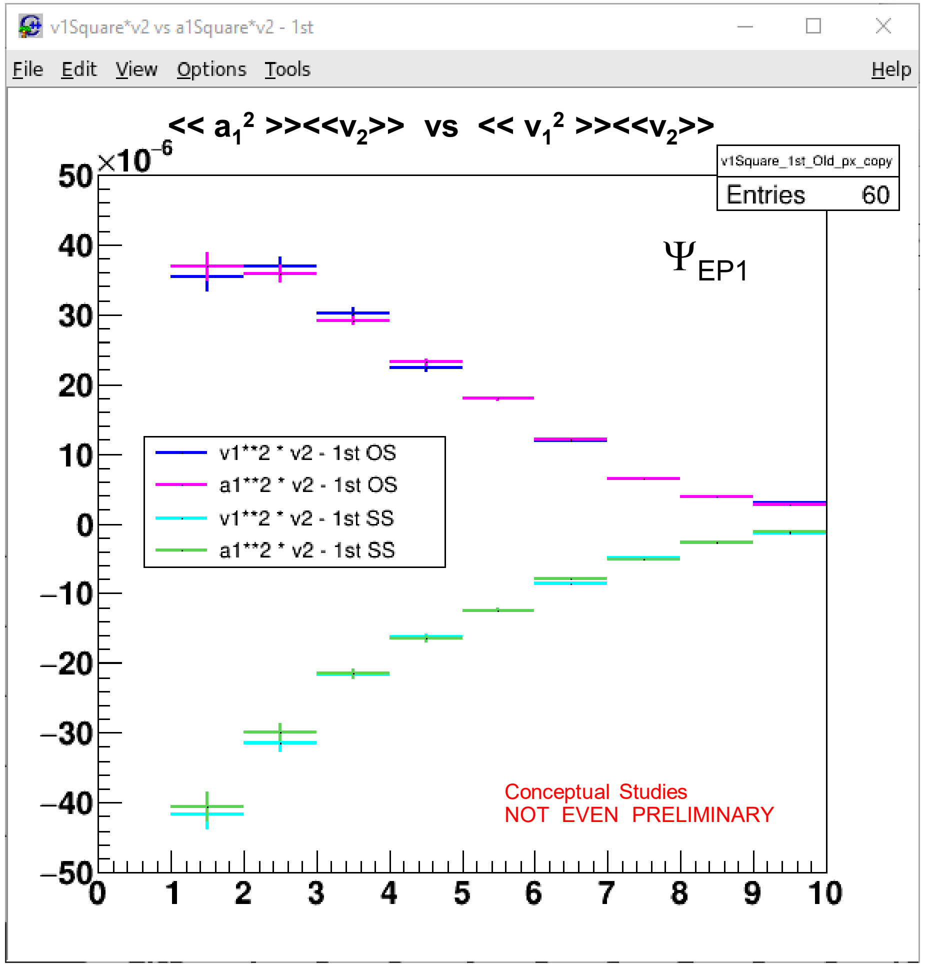


- The notation a_1^2 denotes the EbyE quantity $\Sigma\,(a_{1\_p1}{*}a_{1\_p2})$ with $p1 \neq p2$
- a_1^2 is similar in shape and magnitude to v_1^2 , independent of which EP is used in the study
- a_1^2 shows charge separation … but so does v_1^2 … I didn’t expect to see that

Compare $\langle\langle a_1^2 \rangle\rangle$ and $\langle\langle v_1^2 \rangle\rangle$ [times $\langle\langle v_2 \rangle\rangle$]

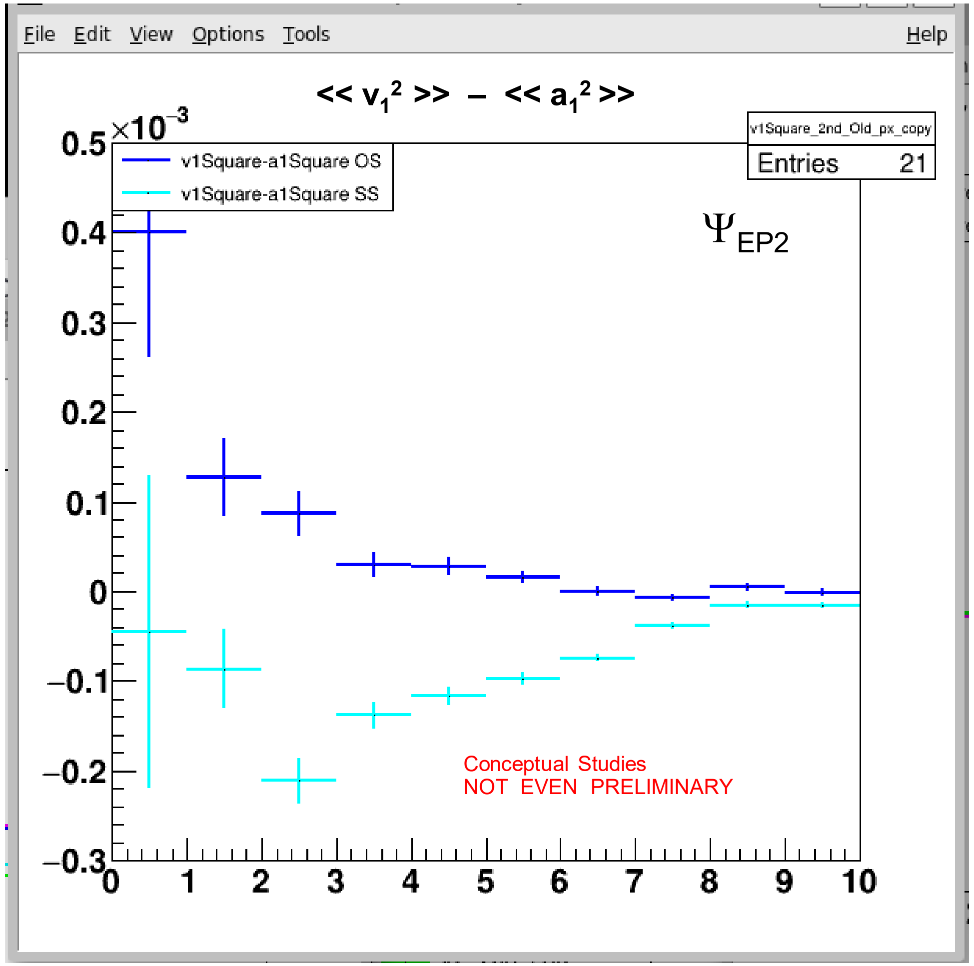
CME signal?

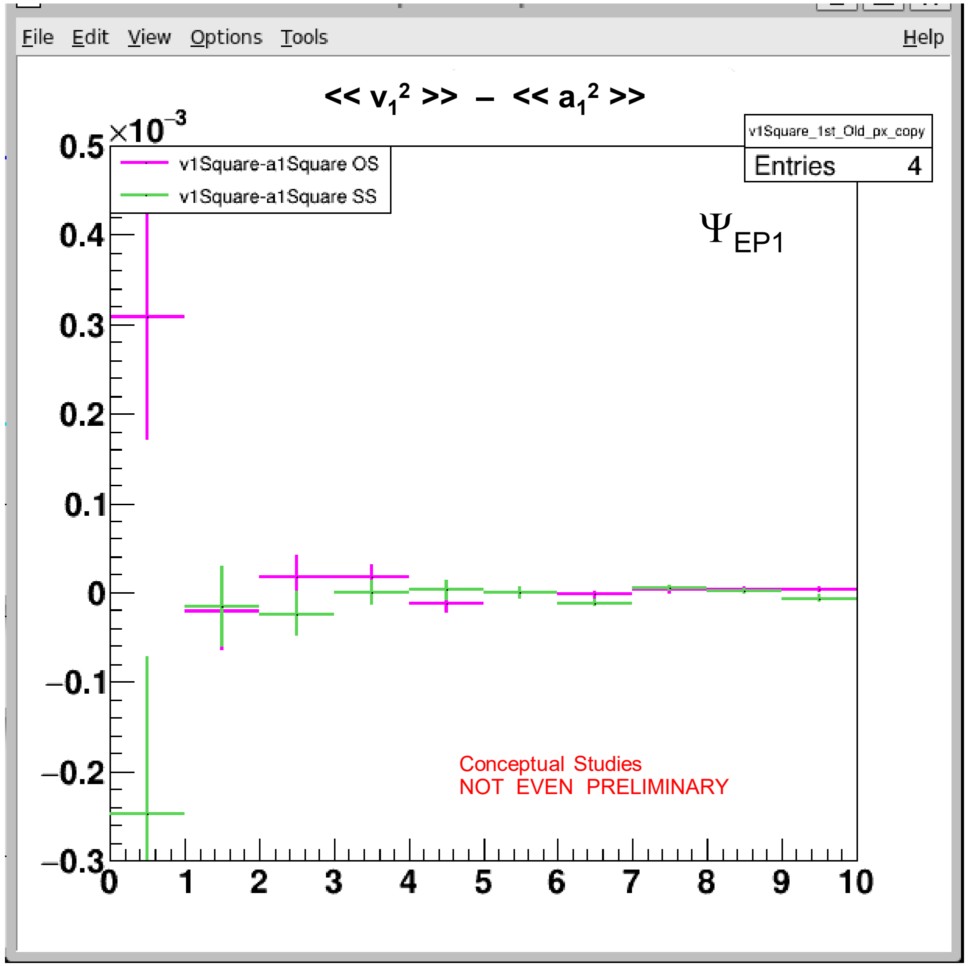




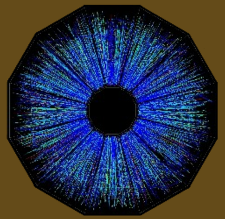
- $\langle\langle a_1^2 \rangle\rangle * \langle\langle v_2 \rangle\rangle$ is similar in shape and magnitude to $\langle\langle v_1^2 \rangle\rangle * \langle\langle v_2 \rangle\rangle$ (note global avg)
- $\langle\langle a_1^2 \rangle\rangle * \langle\langle v_2 \rangle\rangle$ shows charge separation … but so does $\langle\langle v_1^2 \rangle\rangle * \langle\langle v_2 \rangle\rangle$
- I didn't expect to see that …

a_1^2 and v_1^2 from the 200 GeV Au-Au Run 19

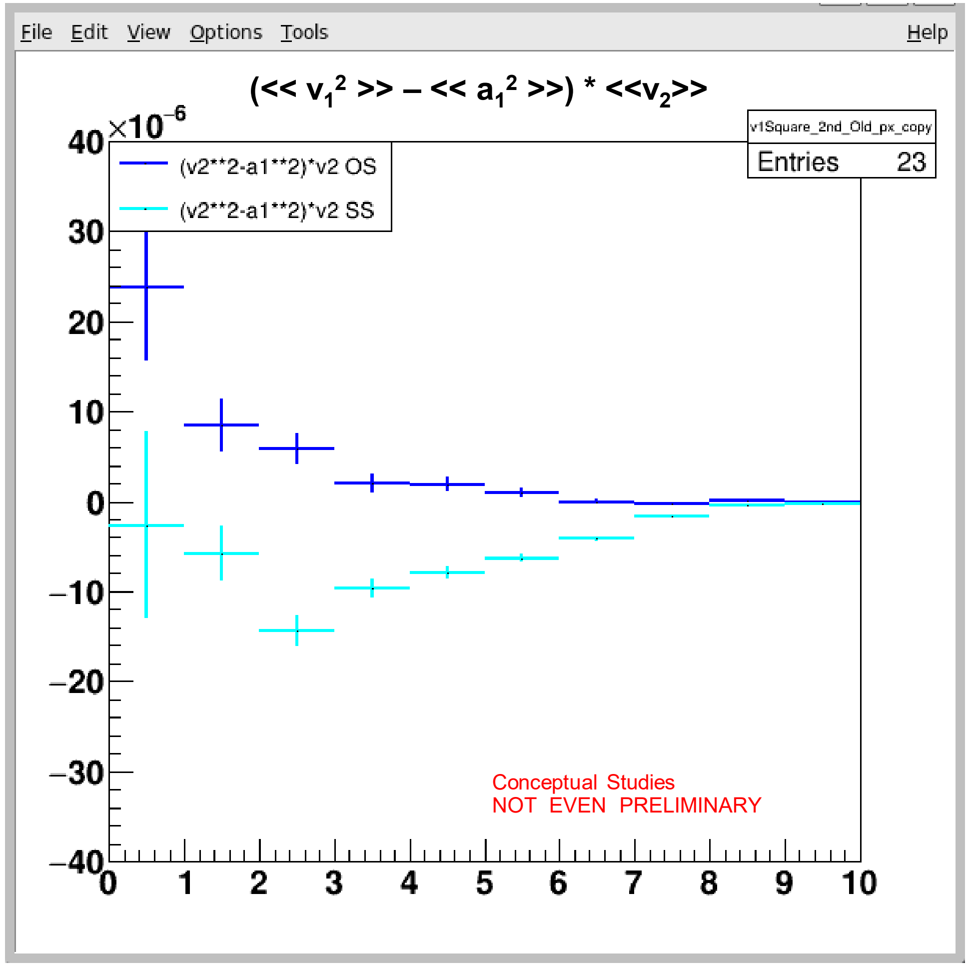


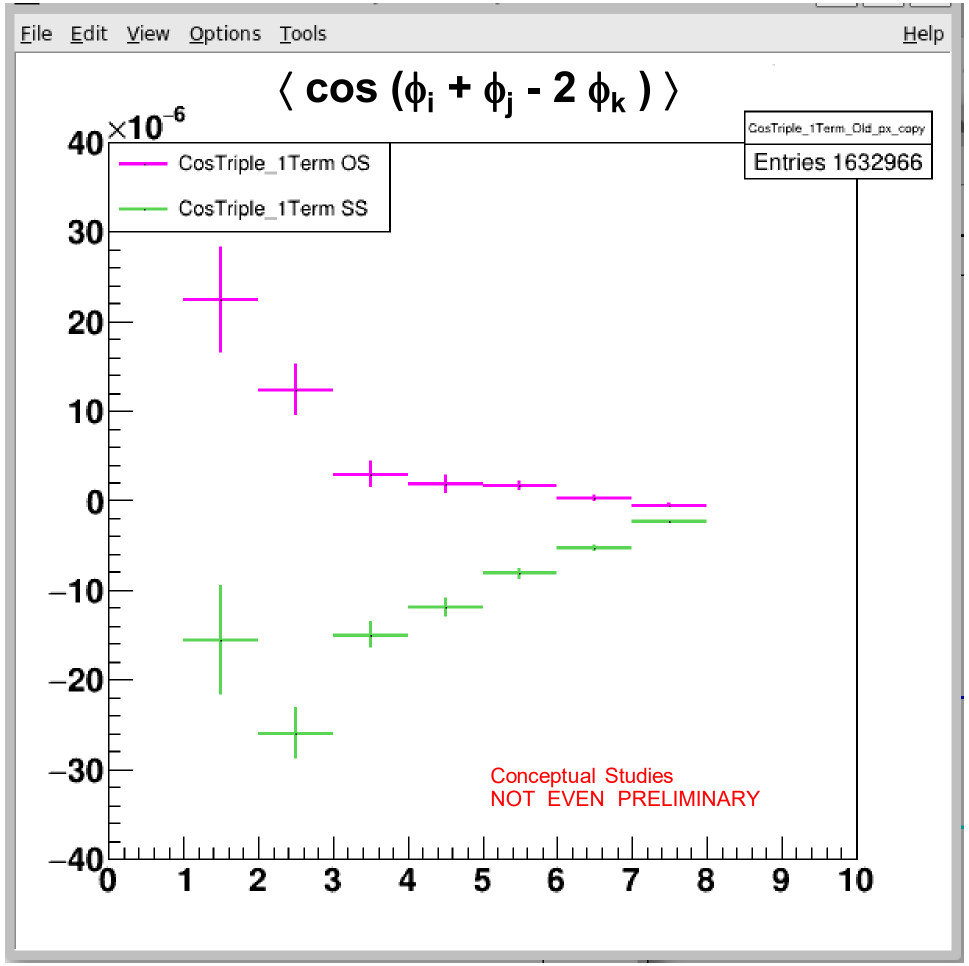


$(v_1^2 - a_1^2)$ with Ψ_{EP2} suggests that SS < 0, OS > 0 while $(v_1^2 - a_1^2)$ with Ψ_{EP1} is ~zero



$(v_1^2 - a_1^2) * v_2$ using Ψ_{EP2} in 200 GeV Au-Au (Run 19)





- Note that $\langle \cos(\phi_i + \phi_j - 2\phi_k) \rangle$ was calculated on an EbyE basis, $\Sigma (v_1^2 - a_1^2) * v_2$
- But, on this page, we are comparing it to $(\langle\langle v_1^2 \rangle\rangle - \langle\langle a_1^2 \rangle\rangle) * \langle\langle v_2 \rangle\rangle$
- The similarity of the curves suggests that the separation of variables is a good approximation and we can focus on $\langle\langle v_1^2 \rangle\rangle - \langle\langle a_1^2 \rangle\rangle$ or simply $\langle\langle a_1^2 \rangle\rangle$ to gather the essential physics

A few thoughts

- $\langle\langle a_1^2 \rangle\rangle$ contains a significant amount of ‘signal’ (i.e. not small)
- $\langle\langle v_1^2 \rangle\rangle$ contains a significant amount of ‘signal’ (i.e. not small)
  - $\langle\langle v_1^2 \rangle\rangle$ is full of signal and similar in shape and magnitude to $\langle\langle a_1^2 \rangle\rangle$
- Both $\langle\langle a_1^2 \rangle\rangle$ and $\langle\langle v_1^2 \rangle\rangle$ show charge separation with OS > 0, SS < 0
  - Not what I had expected
- The difference between these two curves [times $\langle\langle v_2 \rangle\rangle$] is small and similar in shape and magnitude to the γ correlator (Ψ_{RP2})
  - It could be the CME
- Bottom line:
  $\langle\langle v_2 \rangle\rangle$ inside or outside the sum is not important. The physics is in $\langle\langle a_1^2 \rangle\rangle$.
  - What we are really doing is comparing $\langle\langle a_1^2 \rangle\rangle$ to $\langle\langle v_1^2 \rangle\rangle$, using $\langle\langle v_1^2 \rangle\rangle$ as the reference
  - This is a good start … but an assumption. Since $\langle\langle v_1^2 \rangle\rangle$ is large, the physics in the horizontal direction may contain bits not equal to whatever is going on in the vertical direction. Minor bits may overwhelm the CME. This is obvious to expert observers.

A new idea …

- If our goal is to isolate a_{1CME} then we could try focusing directly on $\langle\langle a_1^2 \rangle\rangle$ and work to understand its various components.
  - Currently, we are comparing $\langle\langle a_1^2 \rangle\rangle$ to the same quantity calculated with the EP at 90 degrees. It could also be done with a random EP angle to define the reference signal
  - Or, use mixed events to create another form of a random EP, or the EP from the previous event

- STAR: we can directly compare the isobar systems $\langle\langle a_1^2 \rangle\rangle_{Ru}$ and $\langle\langle a_1^2 \rangle\rangle_{Zr}$
  - Perhaps immune to some of the background issues introduced by $\langle\langle v_1^2 \rangle\rangle$ and/or $\langle\langle v_2 \rangle\rangle$
  - Measure the event planes using multiple independent detectors such as the EPD
  - It is likely that nuclear shapes, flow & multiplicity differences will play a role but this can be evaluated

Backup Slides

Technical notes

- The event planes were calculated using the TPC data, only.
- Centrality bins are preliminary, not the official Run 19 determination.
- The data for $\langle \cos(\phi_i + \phi_j - 2\phi_k) \rangle$ in the centrality bins 0-5% and 5-10% (pg 8) have been explicitly suppressed because they are expensive to calculate in a triple correlation. These are central events and we expect the result to be zero.
- Data taken from one run (~1.8 M Evts Run 19). This is a curse and a blessing: it makes the acceptance corrections stable but results could be a statistical fluke.
- Pion data, selected by 2σ cut on dE/dx band
- In principle, v_1 and a_1 should be measured wrt the 1st order reaction plane, v_2 should be measured wrt the 2nd order EP. If we take the1st order EP results seriously then the charge separation signal is zero. Would be good to do this again with a high quality measure of the 1st order RP such as the EPD
- It is computationally inefficient to calculate auto-correlations for a three particle correlation (especially when using TPC data). We could use independent 1st and/or 2nd order EP determination (e.g. the EPD) which would simplify the auto-correlation corrections. Food for thought and an obvious next step.

Future: one thing that STAR can do almost immediately …

- $\langle\langle v_1^2 \rangle\rangle - \langle\langle a_1^2 \rangle\rangle$ contains the same information as $\langle \cos(\phi_i + \phi_j - 2\phi_k) \rangle$

  $$\langle \cos(\phi_i + \phi_j - 2\phi_k) \rangle = \langle\langle (v_1^2 - a_1^2) * v_2 \rangle\rangle + \text{(other terms)}$$

  and since separation of variables appears to be a good approximation,

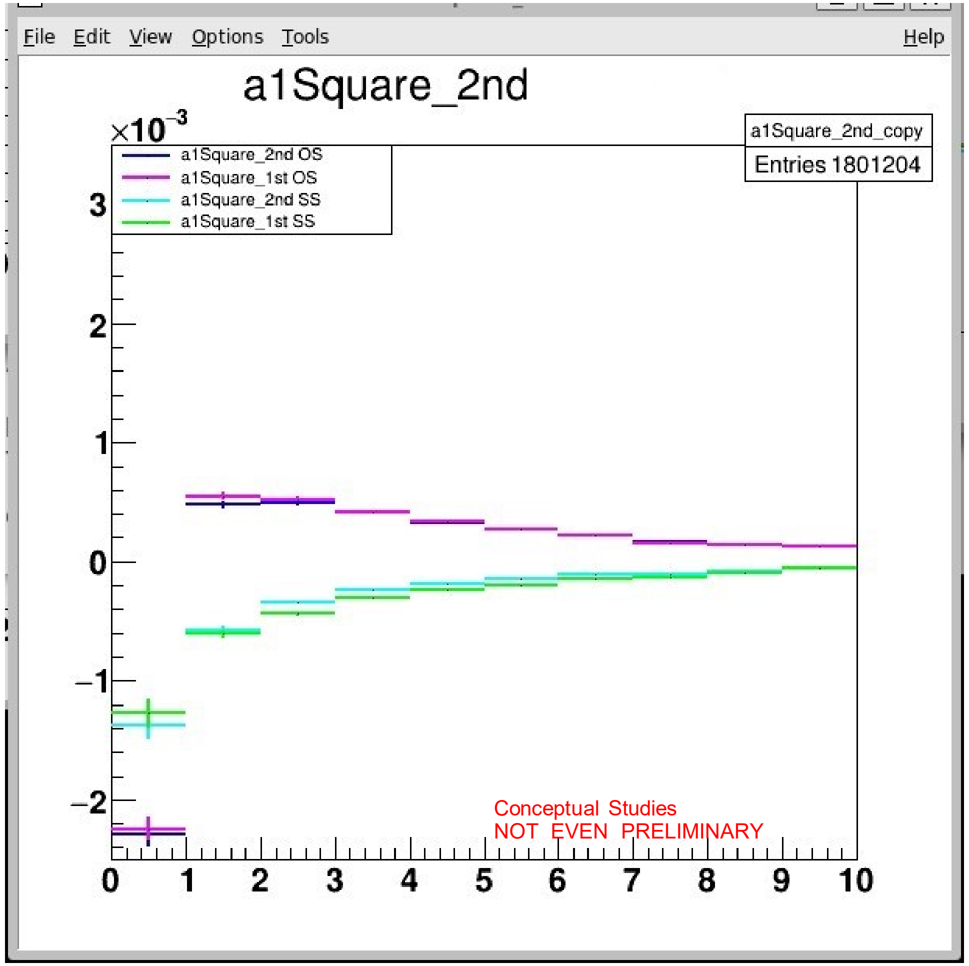
  $$\Rightarrow (\langle\langle v_1^2 \rangle\rangle - \langle\langle a_1^2 \rangle\rangle) * \langle\langle v_2 \rangle\rangle$$

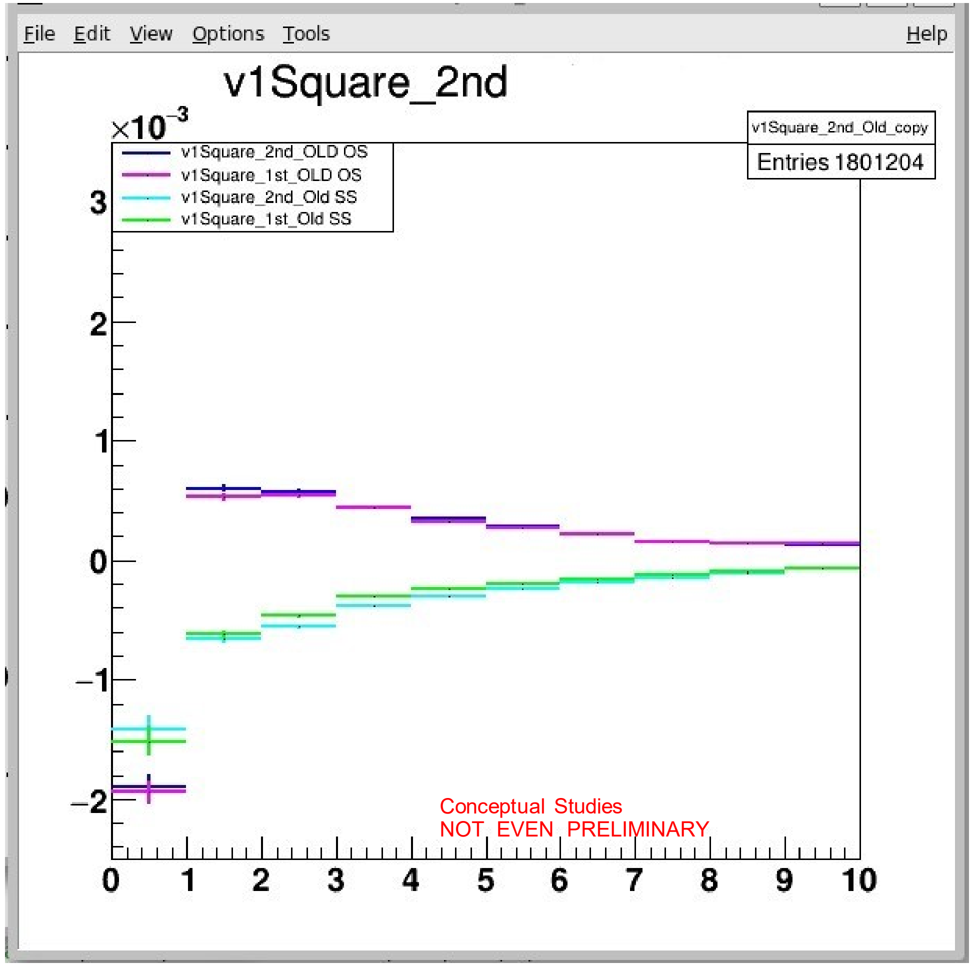
- If we want to isolate a_{1CME} then we could try focusing directly on $\langle\langle a_1^2 \rangle\rangle$ and work to understand its various components. This might avoid background introduced by $\langle\langle v_1^2 \rangle\rangle$ and/or $\langle\langle v_2 \rangle\rangle$.

- If $\langle\langle a_1^2 \rangle\rangle = \langle\langle (a_{1CME} + a_{1background})^2 \rangle\rangle$, then we might assume that $\langle\langle v_1^2 \rangle\rangle$ is a first order approximation to the non-CME components
  - However, we should then explore deviations in the background between the horizontal and vertical directions. Multiplicity fluctuations, flow, and nuclear shapes will likely cause a difference, also nuclear opacity and plasma thickness in the horizontal and vertical directions, detector acceptance
  - A guide might be to consider two colliding stars, or galaxies. Classical matter collisions may inspire additional thoughts about how the horizontal and vertical "background" might be different.

- Even simpler: compare the isobar systems $\langle\langle a_1^2 \rangle\rangle_{Ru}$ and $\langle\langle a_1^2 \rangle\rangle_{Zr}$
  - It is likely that nuclear shapes (etc) will play a role but this is probably a more direct physics result than having to include the $\langle\langle v_1^2 \rangle\rangle$ terms in the discussion
  - And, measure the event plane using an independent detector such as the EPD

a_1^2 and v_1^2 from the 200 GeV Au-Au Run 19





- The notation a_1Square denotes the EbyE quantity $\Sigma\,(a_{1\_p1} * a_{1\_p2})$ with $p1 \neq p2$
- a_1^2 shows charge separation … but so does v_1^2 … I didn't expect to see that