CME Focus Group

(updated with a new figure and a backup slide)

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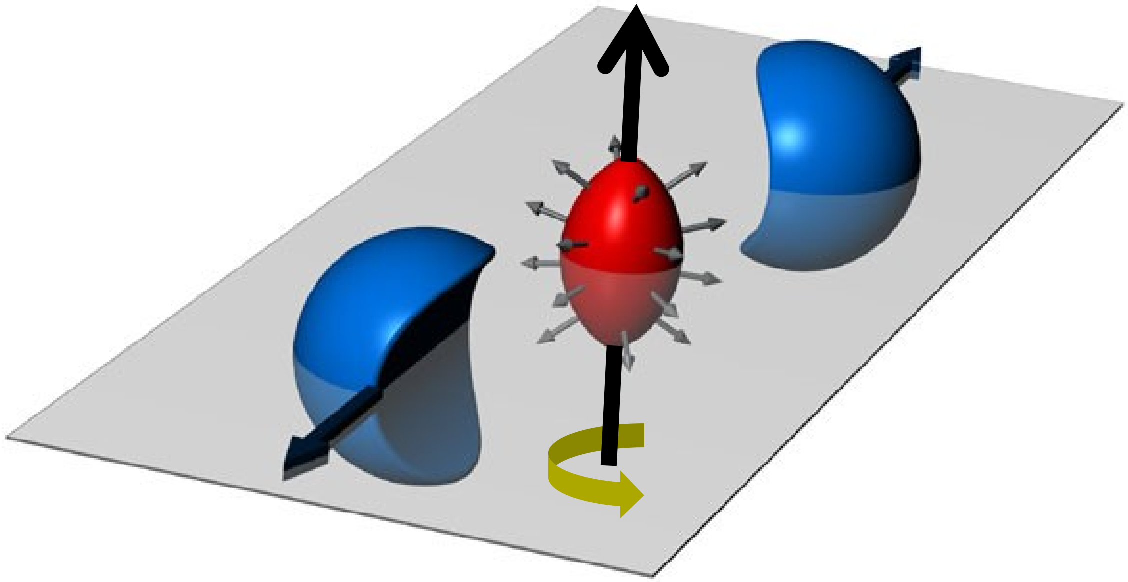
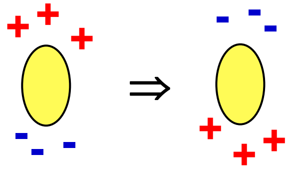
February 17th, 2023

CME: Separation of Charge with respect to the reaction plane

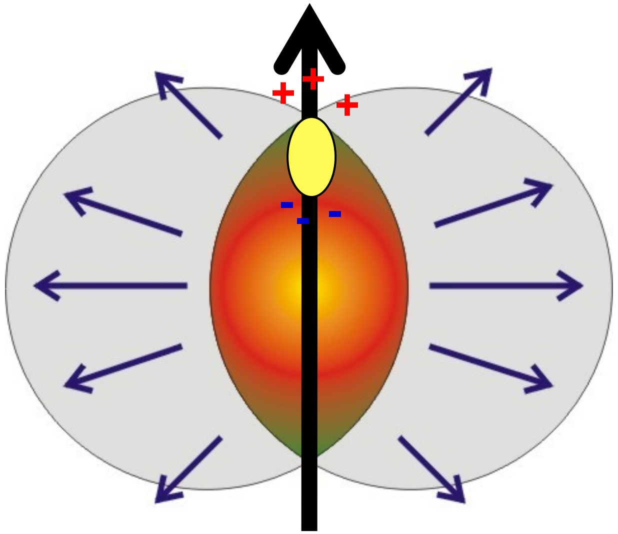


- If a chirally restored bubble is created in a heavy ion collision, the positively charged quarks will go up … then hadronize … and yield an excess of positive pions above the plane
- Unfortunately, it could be just the opposite in the next event depending on the topological charge in the bubble

- 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 <u>correlation techniques</u>



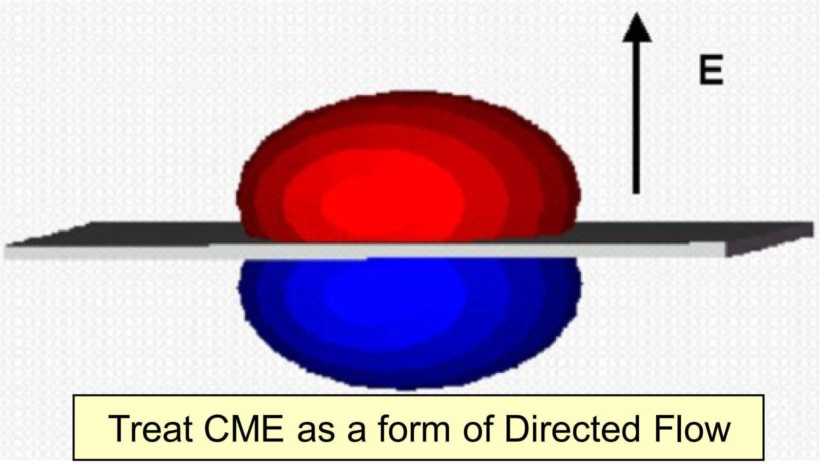
The observable and the tools for analysis

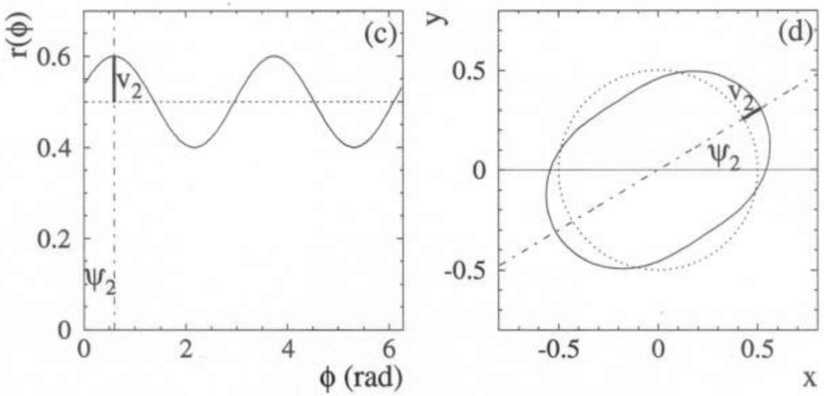
n=1: Directed Flow has a period of 2π (only one maximum)

- 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

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





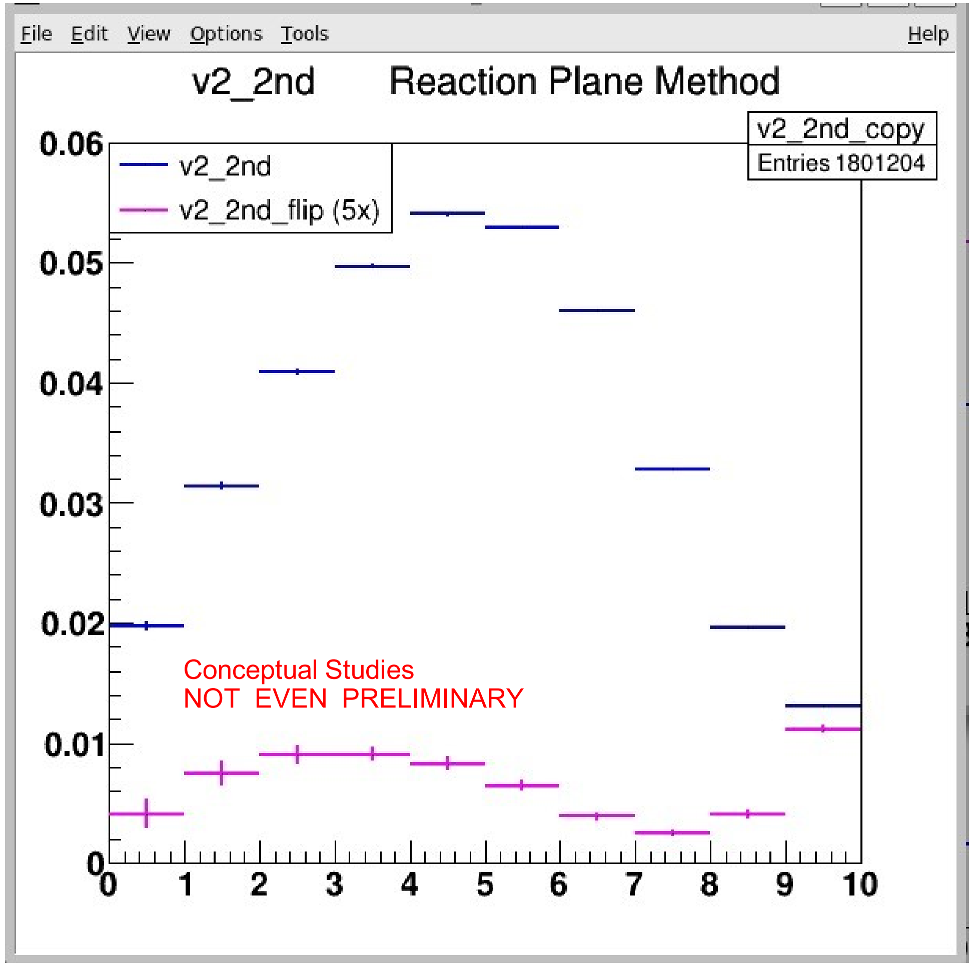
sin() terms may be non-zero if parity isn't conserved

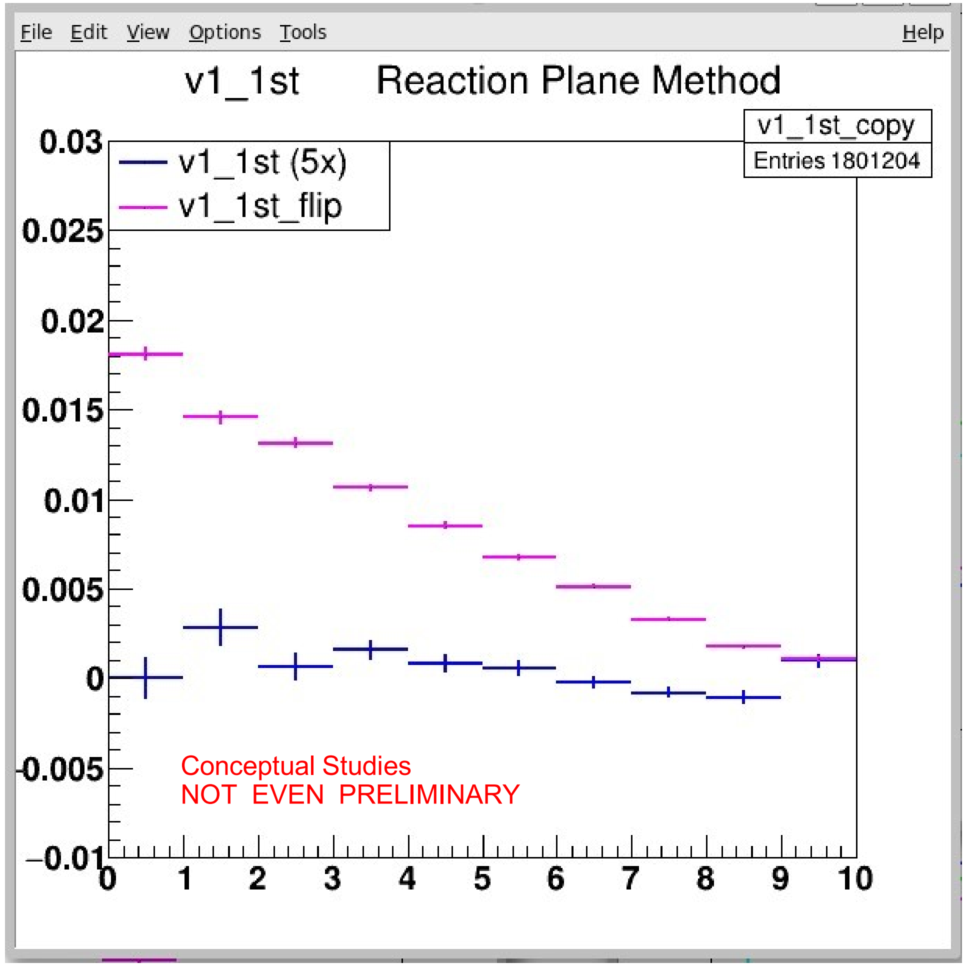
Perform a Fourier Transform to isolate the coefficients

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

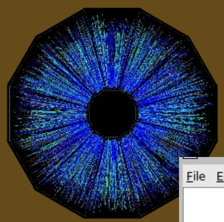
isotropic | **parity non-conserving** | **directed** | **h.o. nc terms** | **elliptic** | **higher order terms**

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

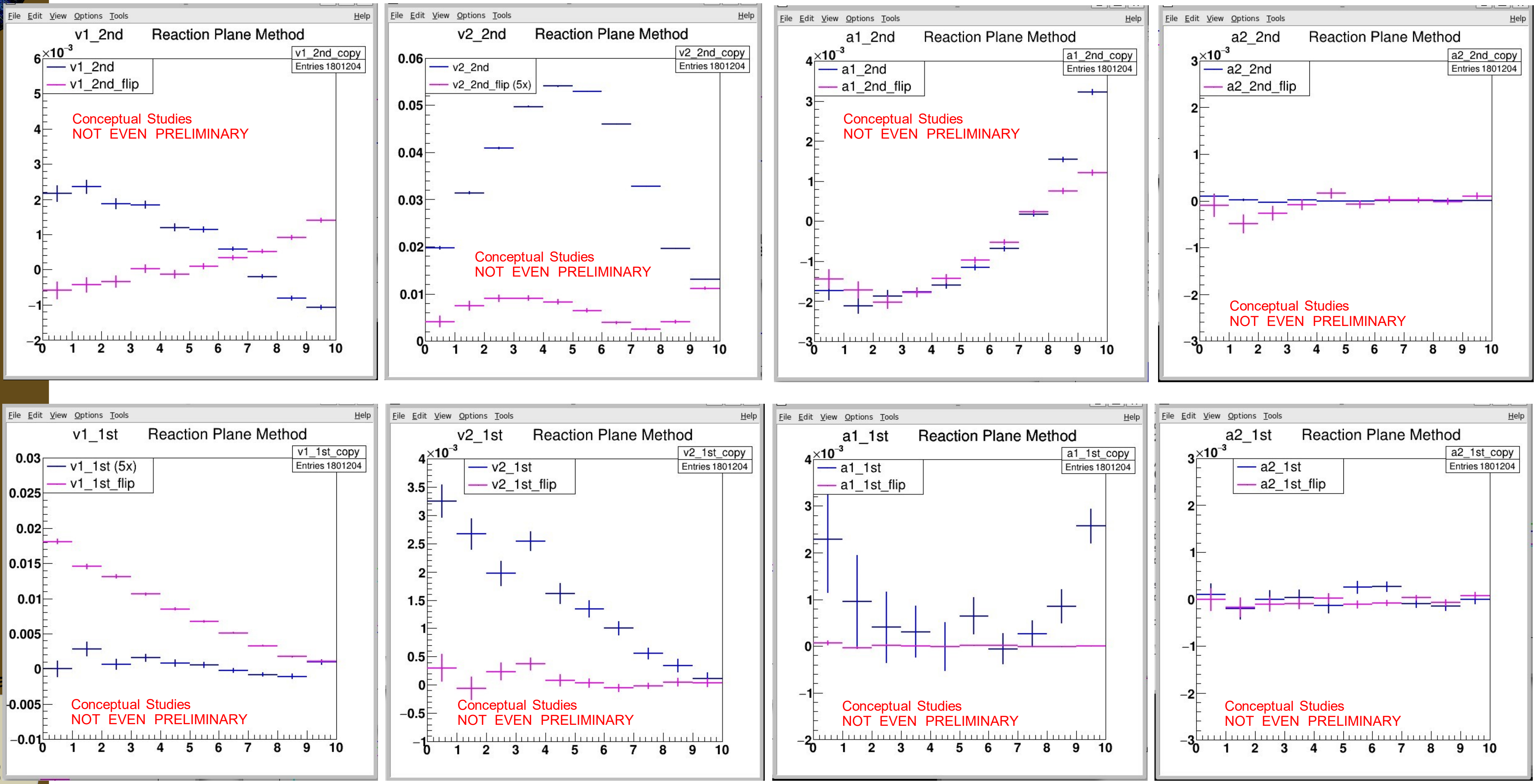




v_1 and v_2 doing familiar things (Note: Ψ_1 & Ψ_2 RPs measured in TPC)



Several more low order terms …



The γ observable

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

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

  – where the average is taken over all particles in the event and ψ_R is the known reaction plane angle (e.g. from the TPC or the EPD)
  – The equation on the right is a multi particle correlation

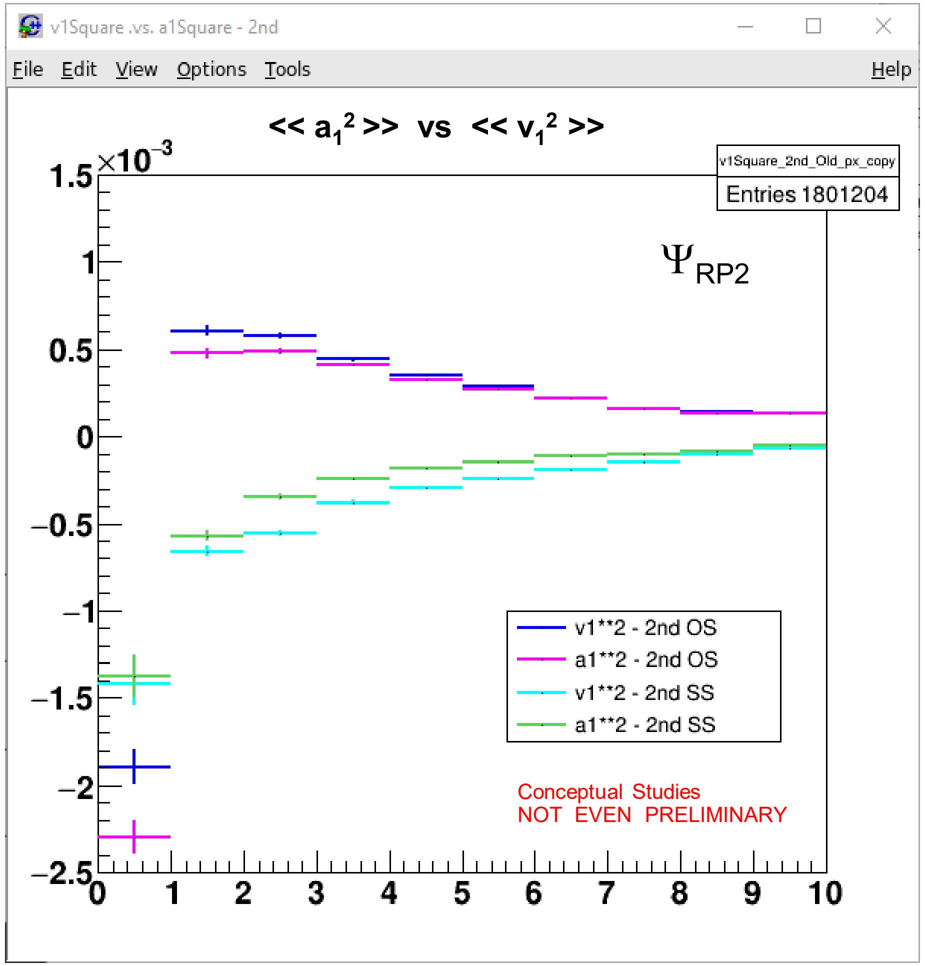
- Under certain assumptions v_1 is directed flow
  – Note that 'normal' v_1 measurements in a symmetric Au-Au collision have an intrinsic symmetry that requires weighting by sign(η) to measure $v_{1\ \mathrm{Hydro}}$
  – Tool: look for charge flow (up/down) without sign(η) weighting because $v_{1\ \mathrm{Hydro}}$ will cancel out if we have symmetric η acceptance.

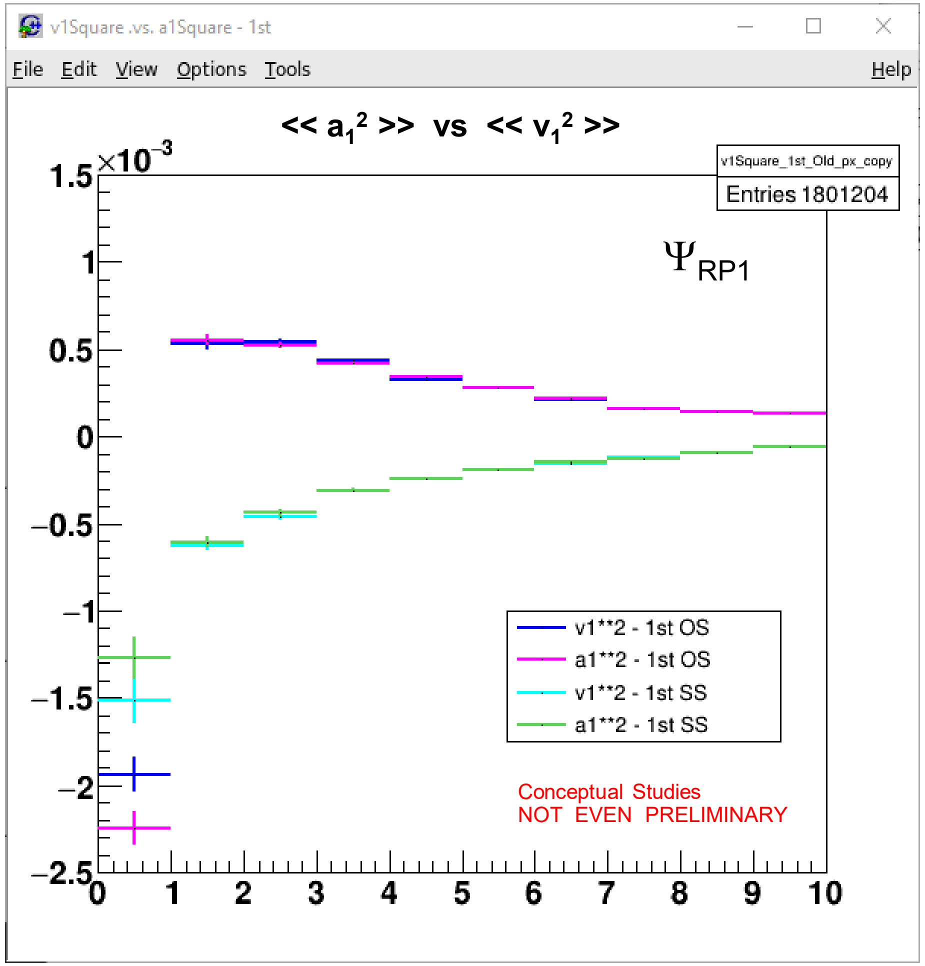
- γ is a clever observable. A triple correlation $\Rightarrow \langle \cos(\phi_i + \phi_j - 2\phi_k) \rangle$
  – Mixed Harmonics: $\langle \cos(\varphi_i - \varphi_k)\cos(\varphi_j - \varphi_k) - \sin(\varphi_i - \varphi_k)\sin(\varphi_j - \varphi_k) \rangle = (v_1^2 - a_1^2)\, v_2 + \ldots$
  – A 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:

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

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

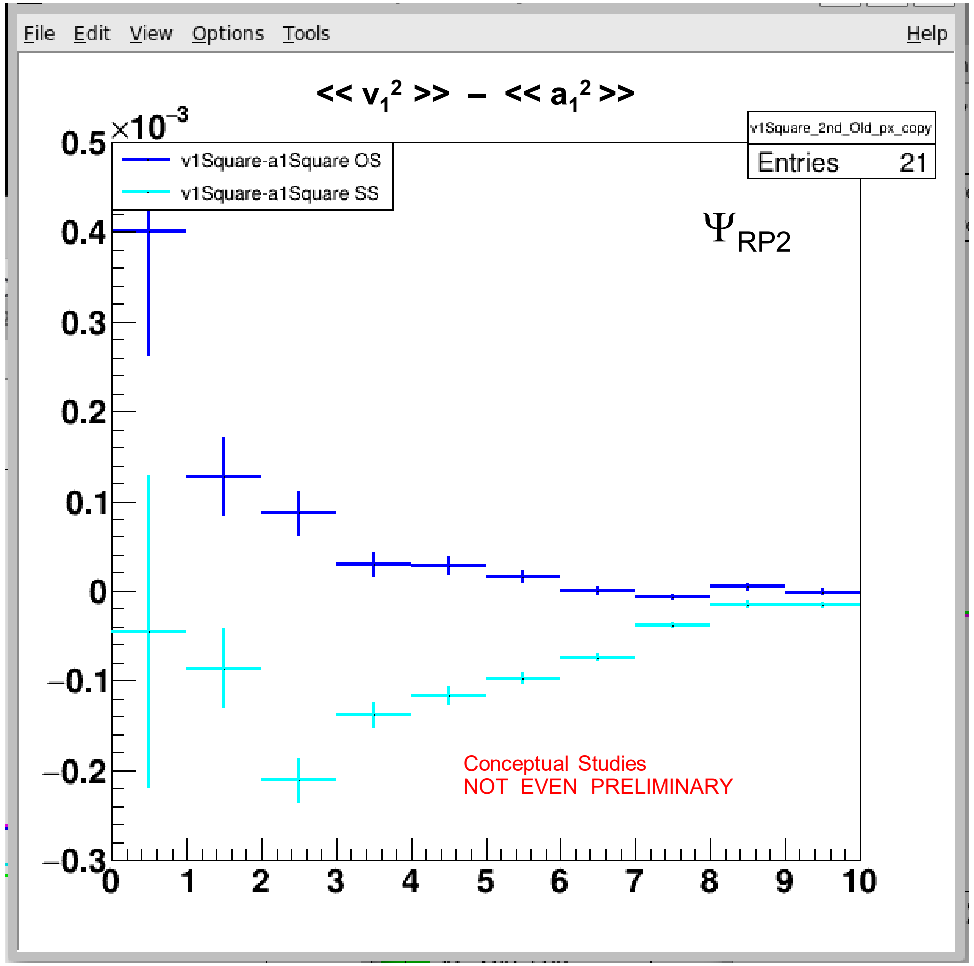
a_1^2 and v_1^2 from the 200 GeV Au-Au Run 19

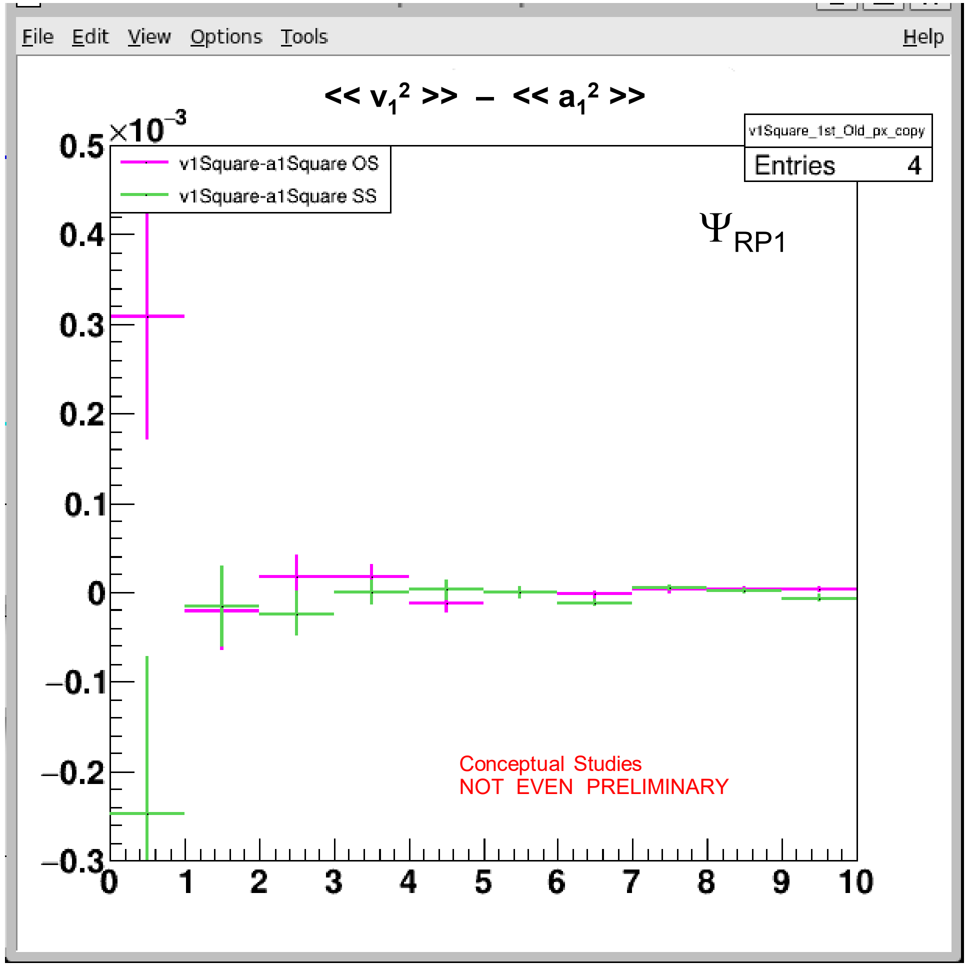




- The notation a_1^2 denotes the EbyE quantity $\Sigma\,(a_{1\_p1} * a_{1\_p2})$ with $p1 \neq p2$
- a_1^2 is similar in shape and magnitude to v_1^2, independent of which RP is used in the study
- a_1^2 shows charge separation … but so does v_1^2 … I didn't expect to see that

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



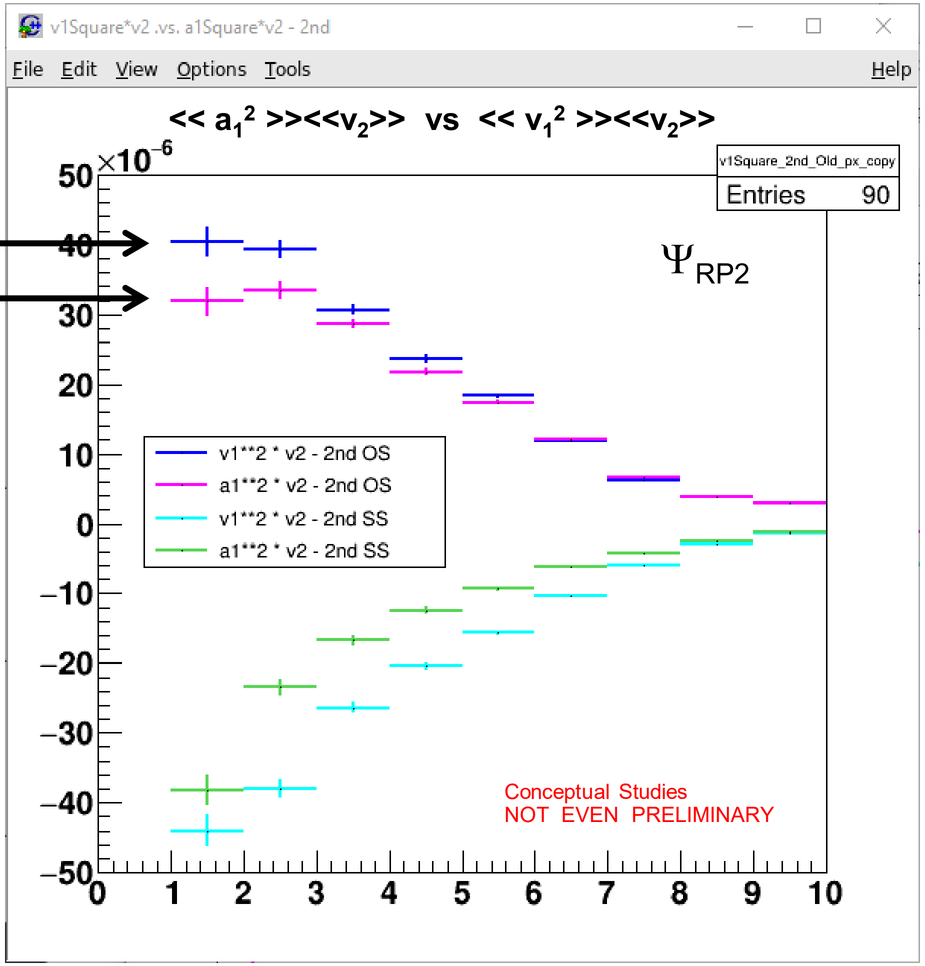


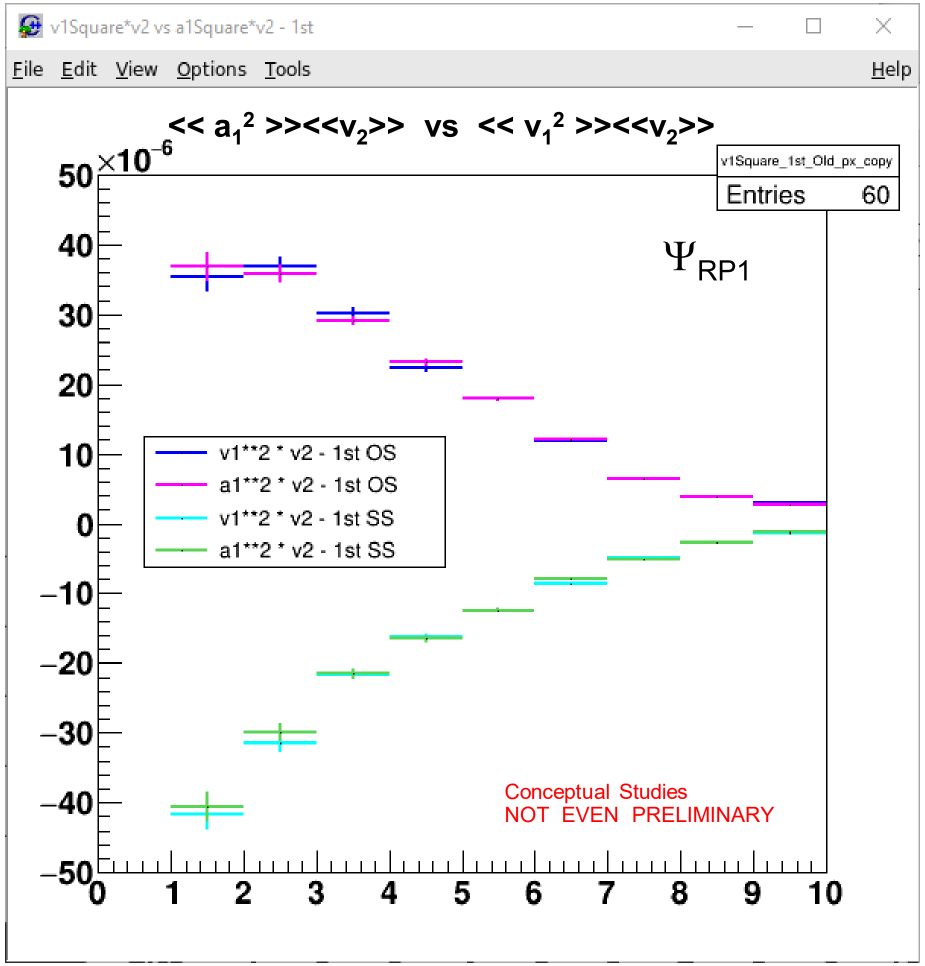
$(v_1^2 - a_1^2)$ with Ψ_{RP2} suggests that SS < 0, OS > 0

while $(v_1^2 - a_1^2)$ with Ψ_{RP1} is ~zero

Compare $<<a_1^2>>*<<v_2>>$ and $<<v_1^2>>*<<v_2>>$

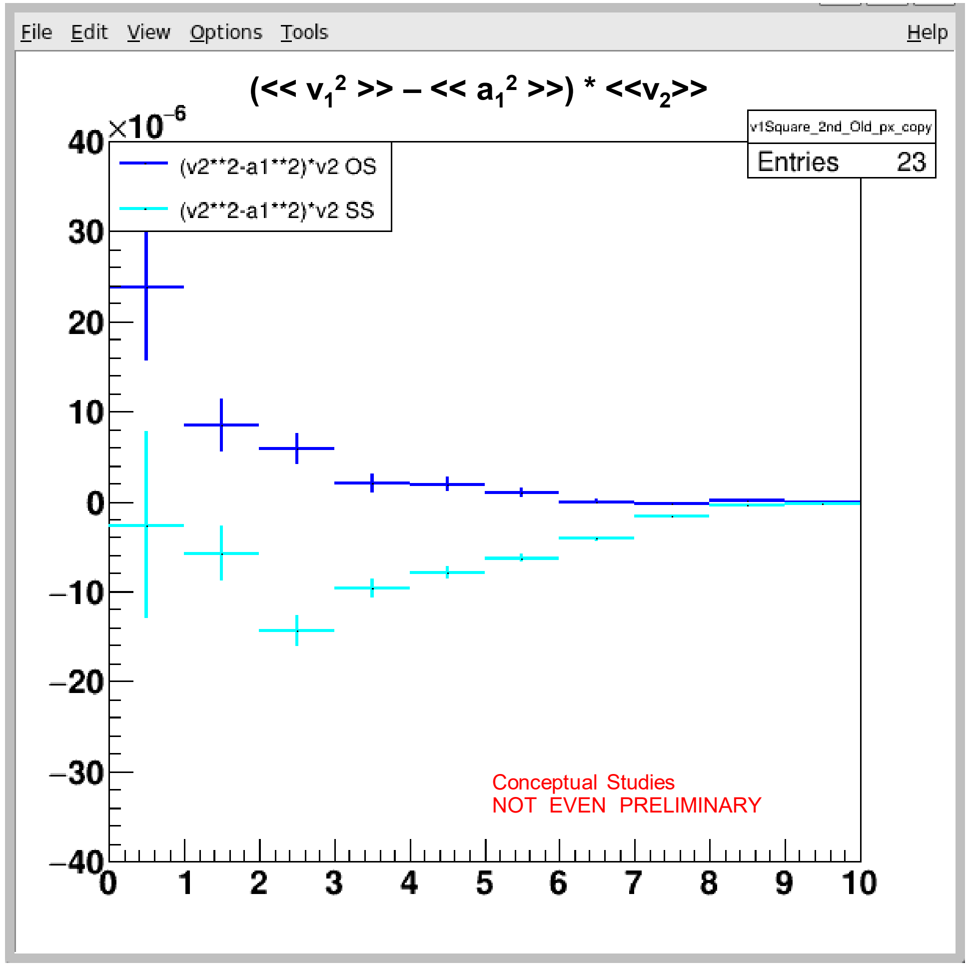
CME signal?

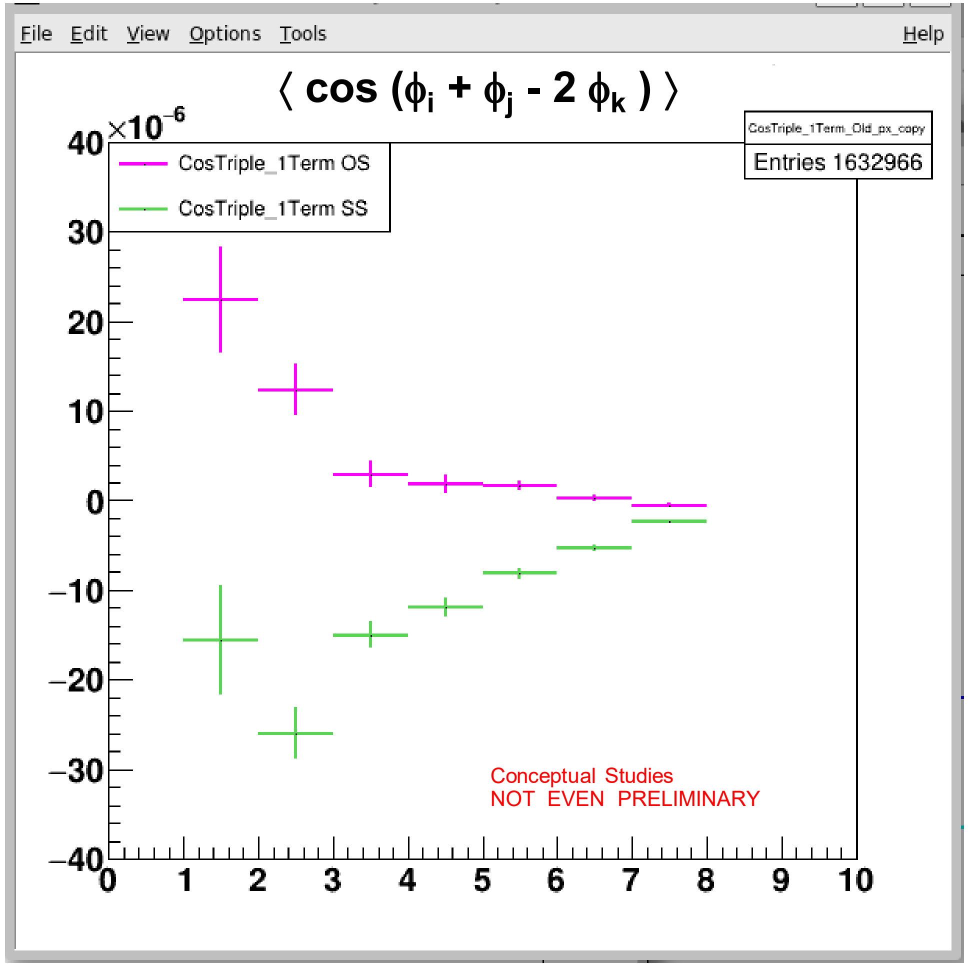




- $<<a_1^2>>*<<v_2>>$ is similar in shape and magnitude to $<<v_1^2>>*<<v_2>>$ (note global avg)
- $<<a_1^2>>*<<v_2>>$ shows charge separation … but so does $<<v_1^2>>*<<v_2>>$
- I didn't expect to see that …

$(v_1^2 - a_1^2) * v_2$ using Ψ_{RP2} 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 curves in the left and right figures are similar in shape and magnitude

Concluding thoughts

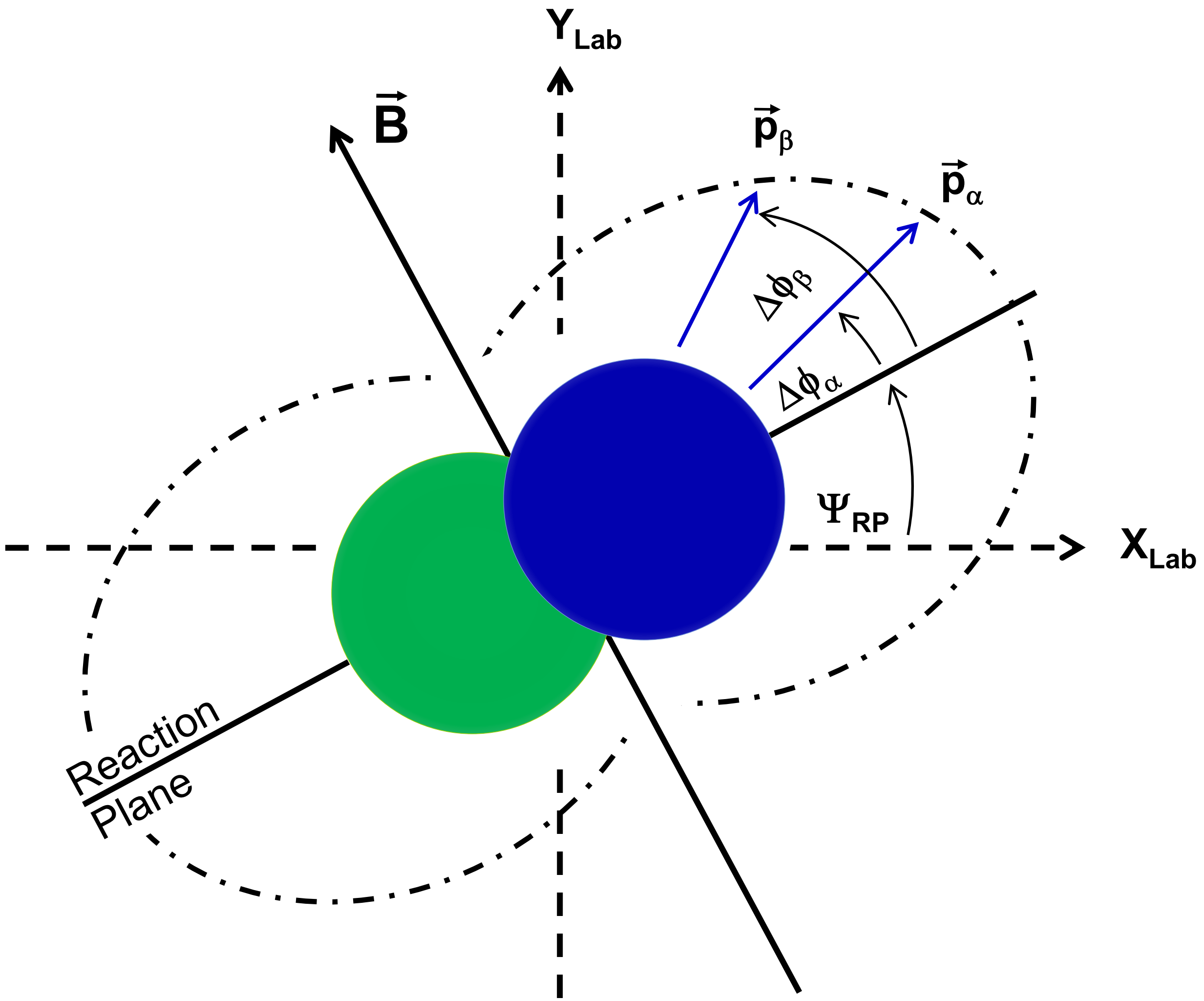
- $<<a_1^2>>$ contains a significant amount of 'signal' (i.e. not small)
- $<<v_1^2>>$ contains a significant amount of 'signal' (i.e. also, not small)
  - $<<v_1^2>>$ is full of signal and similar in shape and magnitude to $<<a_1^2>>$
- Both $<<a_1^2>>$ and $<<v_1^2>>$ show charge separation with OS > 0, SS < 0
  - Not what we expected
- The difference between these two curves times $<<v_2>>$ is small and similar in shape and magnitude to the γ correlator (Ψ_{RP2})
  - It could be the CME
- $(<<v_1^2 - a_1^2>>) * <<v_2>>$ includes a global average for v_2 and not EbyE with the other terms, yet the product looks very similar to $<< (v_1^2 - a_1^2) * v_2 >>$
- The data are not fully consistent with the assumptions put forth at the start of the talk and so we may not be isolating a_{1CME} in the way we had hoped
- Bottom line: we are putting our faith in the subtraction of two large numbers to find a small signal. This could be a risky strategy when looking for new physics.

Technical notes

- The RPs 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 RP. If we take the1st order RP 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 RP determination (e.g. the EPD) which would simplify the auto-correlation corrections. Food for thought and an obvious next step.

Backup Slides

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

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

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

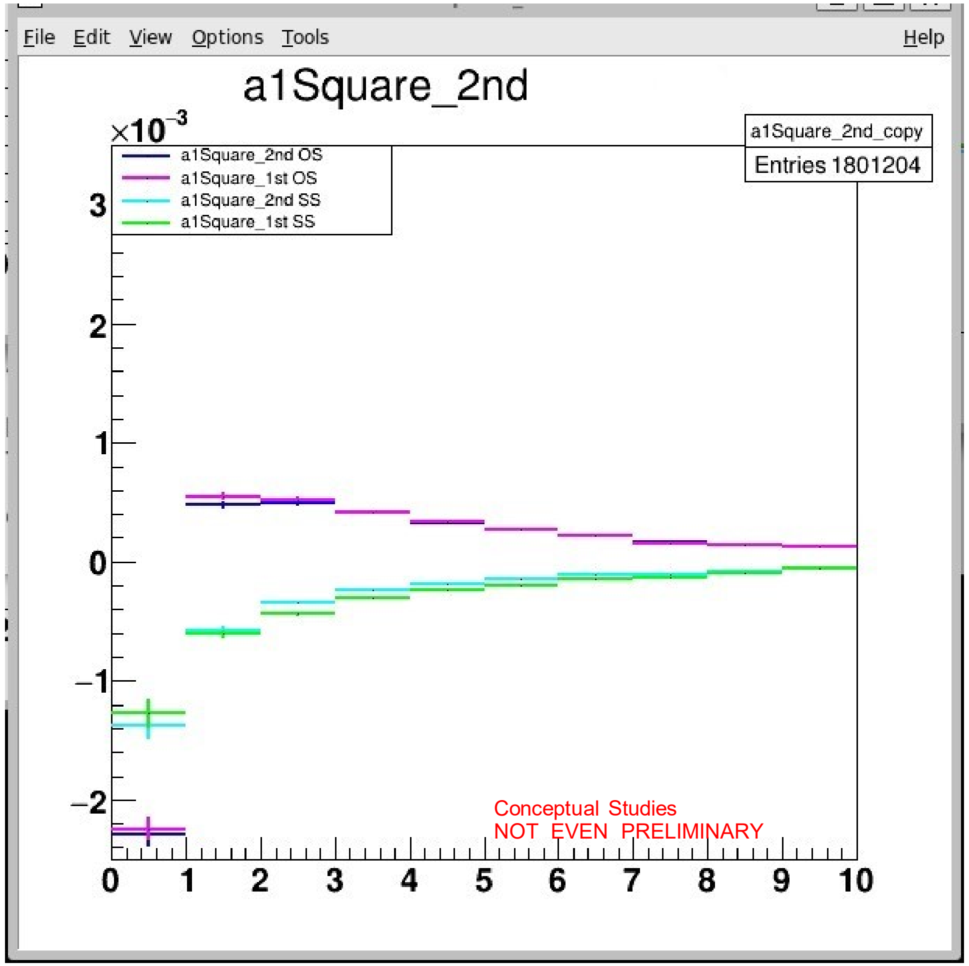
where

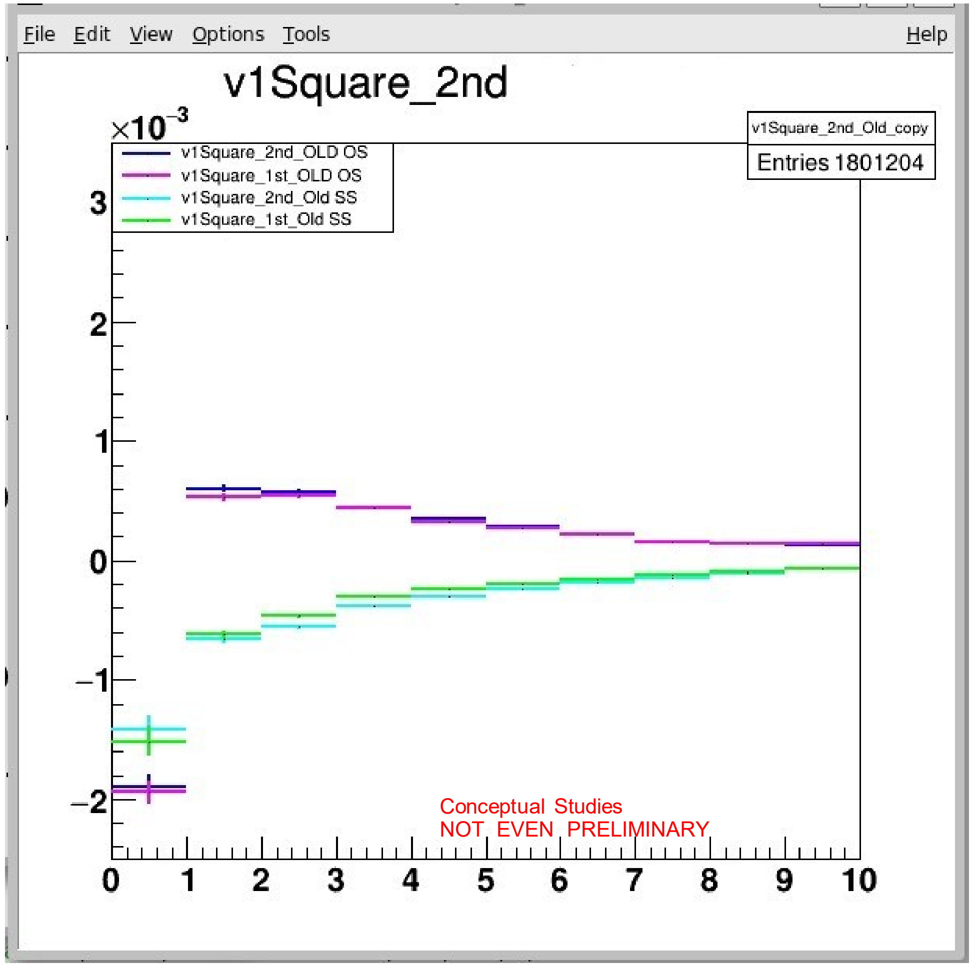
$$a_n = \pi\, a'_n = \sum_i \sin(\, n(\phi_i - \Psi_R)\,)\,, \qquad b_n = \pi\, b'_n = \sum_i \cos(\, n(\phi_i - \Psi_R)\,)$$

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

The Chiral Magnetic Effect

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 $p1 \neq p2$
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