An Independent Look at Parity Violation in the Strong Interaction

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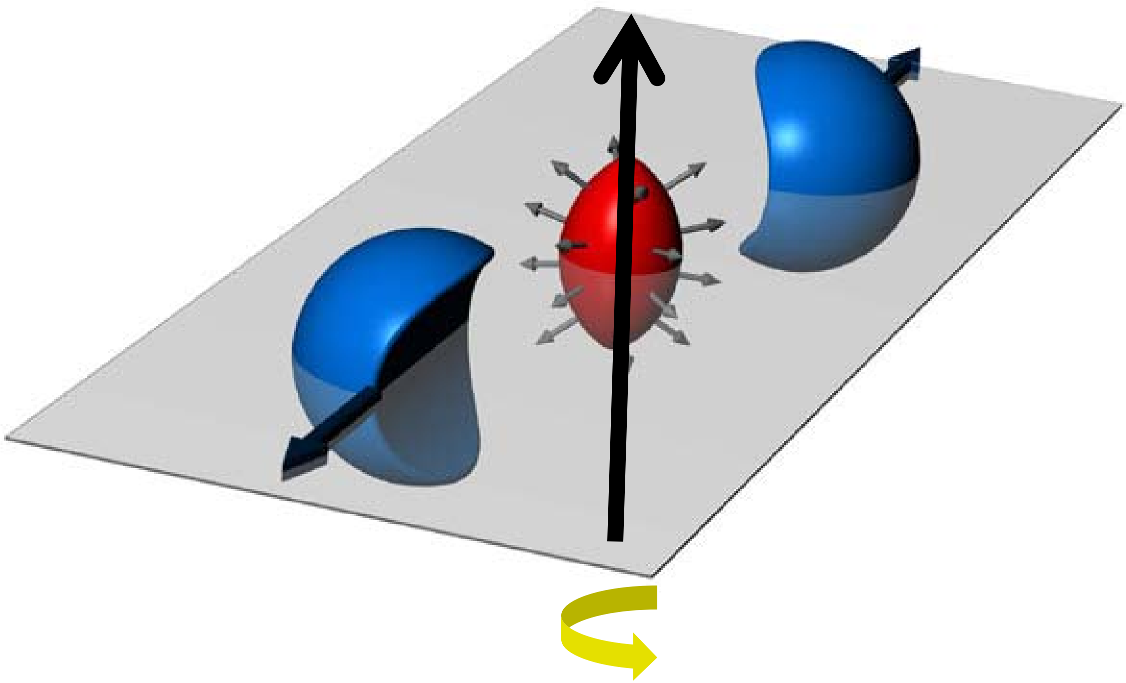
The existing dogma

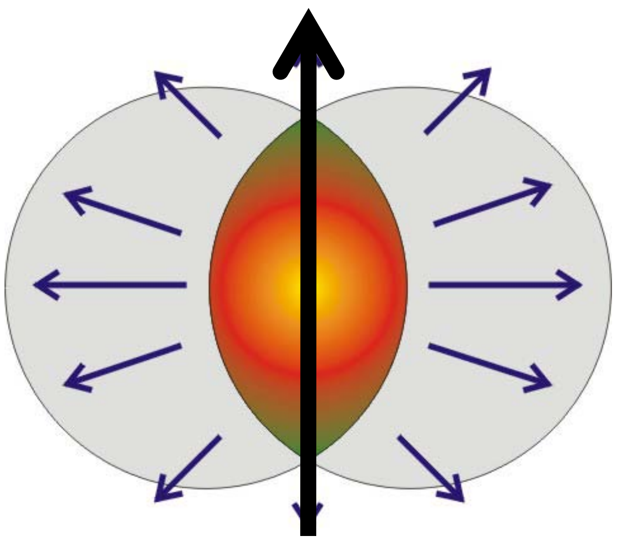
- “Parity is conserved in the strong and electromagnetic interactions”
  – See, for example, Perkins “Introduction to High Energy Physics”

- Lets take a fresh look at heavy ion collisions to see if this dogma is always be true …

Conservation of Global Angular Momentum



- Kharzeev et al. have proposed that angular momentum is (globally) conserved in a heavy ion collision and does not beakup into smaller pieces
- If this is true, then there should be an angular momentum vector that lies perpendicular to the reaction plane



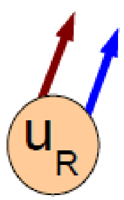
- Electromagnetic charges in motion lead to an electromagnetic magnetic field (not a color magnetic field)
- The magnetic fields can reach 10^{17} gauss. Stronger than on the surface of a neutron star.
- May be related to ridge formation etc.

Quarks interact with the B field via their spin

- **Recall that chiral symmetry is restored in a QGP**
- **Recall that meson masses drop to ~0 after chiral symmetry restoration**

In chiral limit:

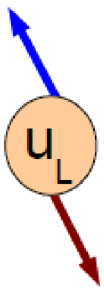
Particles/Antiparticles
with right-handed helicity



have spin and momentum parallel

In chiral limit:

Particles/Antiparticles
with left-handed helicity



have spin and momentum anti-parallel

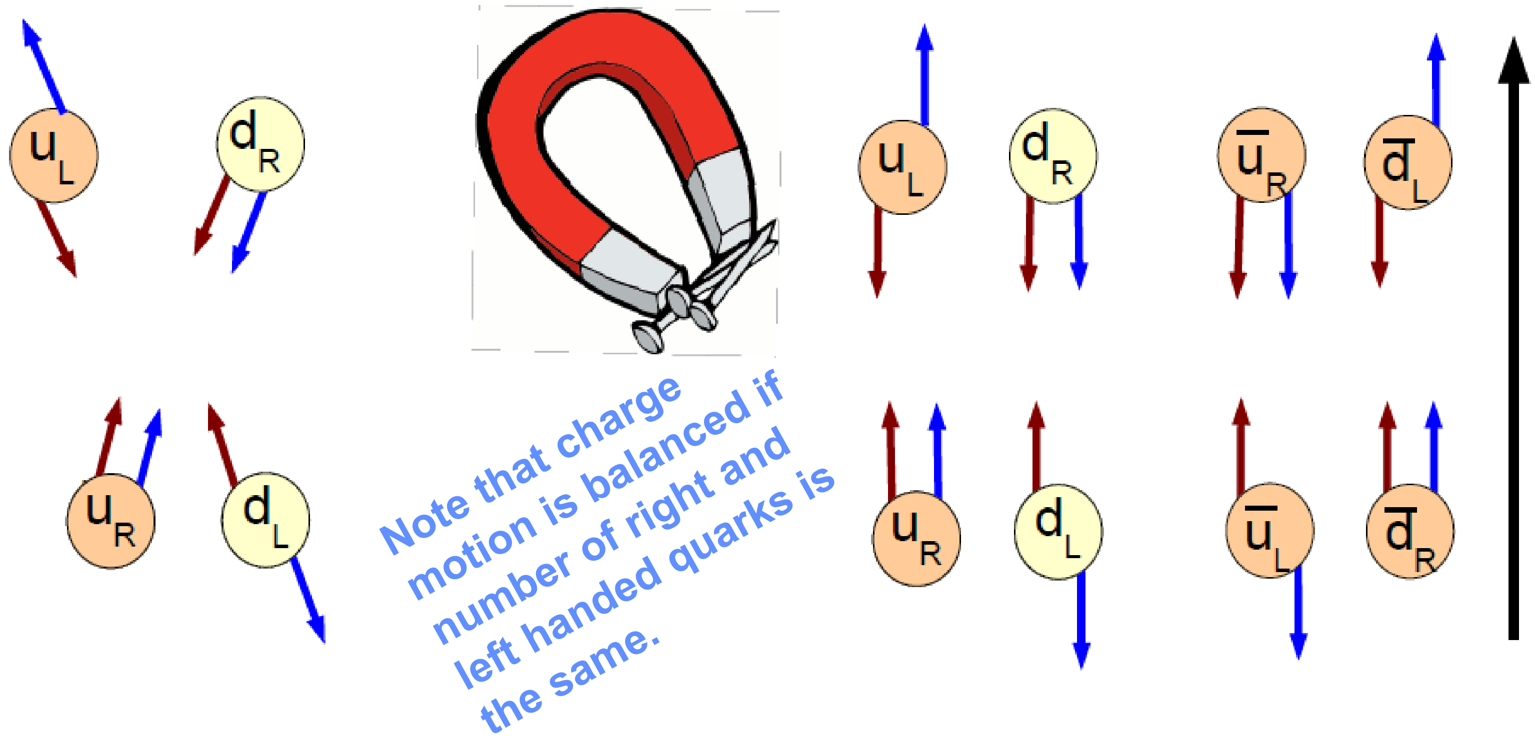
- **Kharzeev et al. assume massless quarks in this study**
- **Chirality and helicity are the same for massless particles … so in the limit of zero mass, it is easy to define chirality (not so easy for non-zero mass).**

How does the B field affect the Quarks?

A magnetic field will align the spins, depending on their electric charge

No Magnetic Field: No polarization

Magnetic field: Polarization B



The momenta of the quarks align along the magnetic field

A quark with right-handed helicity will have momentum opposite to a left-handed one

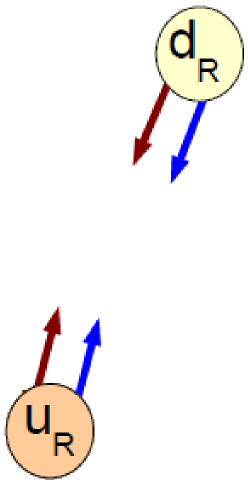
In this way the magnetic field can distinguish between right and left

H. Warringa

How does the Magnetic field affect Chirality?

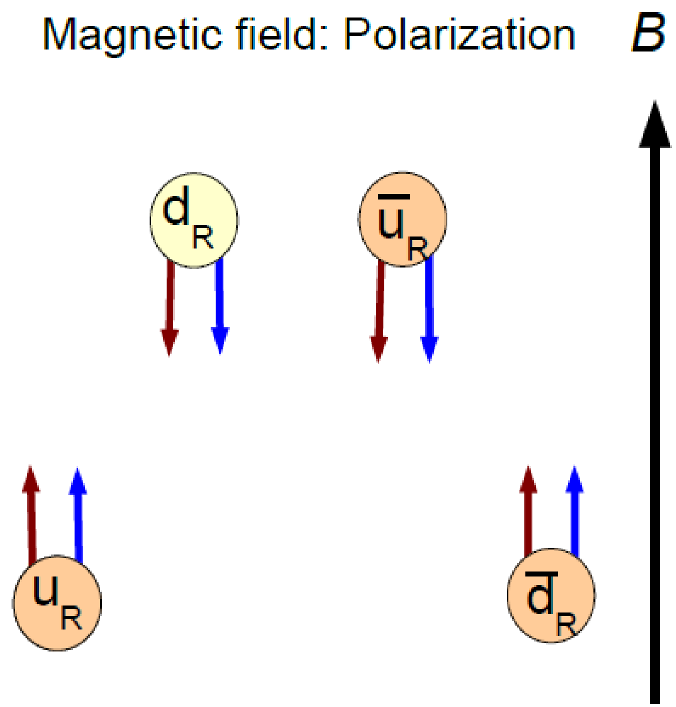
A magnetic field will align the spins, depending on their electric charge

No Magnetic Field: No polarization



Topological Charge fluctuations can create an excess of right, or left handed quarks. Note that right handed quarks move symmetrically up or down based on charge.

Magnetic field: Polarization



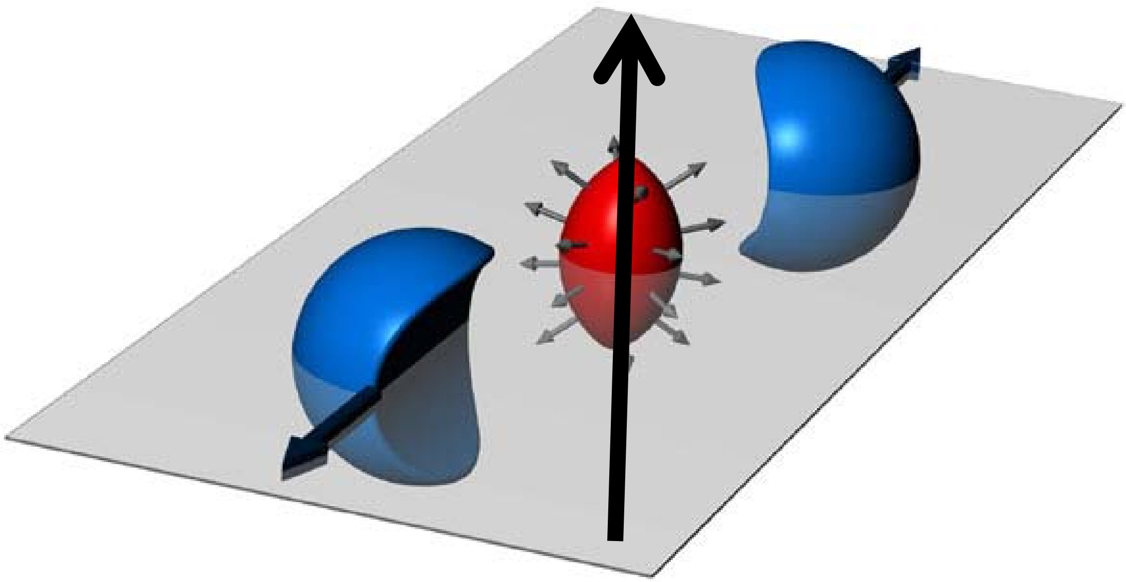
Positively charged particles move parallel the magnetic field

Negatively charged particles move to antiparallel to magnetic field

An electromagnetic current is created along the magnetic field

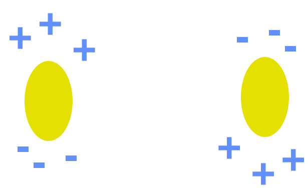
H. Warringa

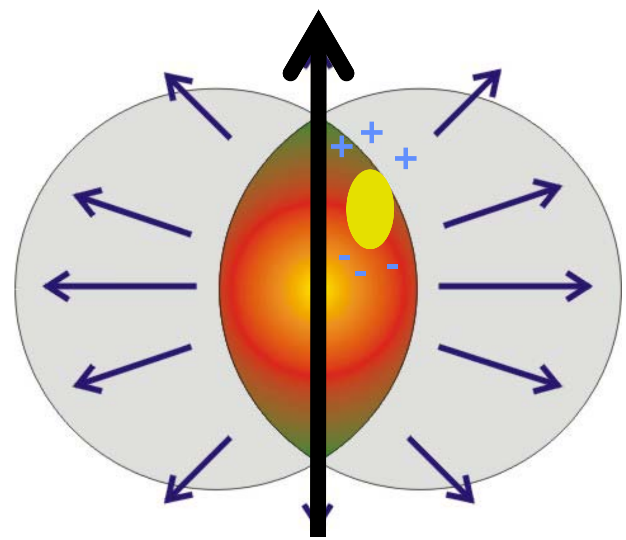
Separation of Charge wrt the reaction plane



- **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 Observables**





- **Can we see this signature of parity violation (and chiral symmetry restoration) with event by event techniques?**

A Full Fourier Transform

STAR

$$f(\phi) = \frac{b'_0}{2} + \sum_{n=1}^{\infty} \left(a'_n \sin(n\phi) + b'_n \cos(n\phi) \right)$$

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 need to 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

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

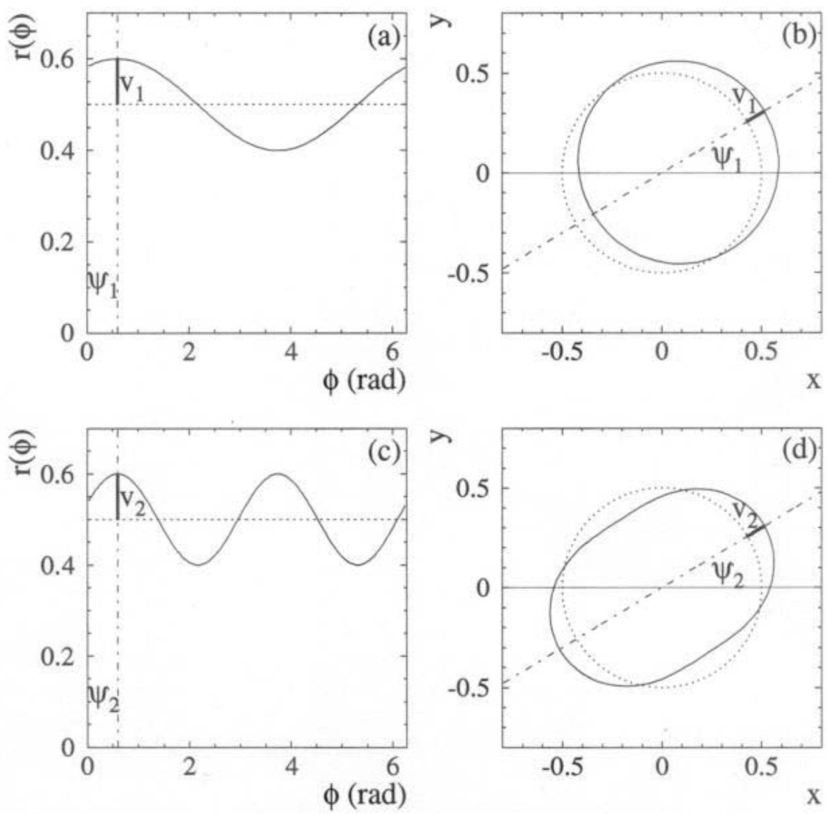
Interpreting Flow – order by order

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 off the collision zone

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

- v_2 represents the elliptical shape of the momentum distribution



Perform a Fourier Transform to isolate the coefficients

If parity is conserved, sin() terms drop out

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

isotropic — parity non-conserving — directed — elliptic — higher order terms

The Signal

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

  $$\mathrm{b}_n \equiv \left\langle \cos(n(\phi - \phi_R)) \right\rangle \quad \textbf{or} \quad b_n^2 = \left\langle \cos(n(\phi_i - \phi_j)) \right\rangle$$

  – **where the average is taken over all particles in the event and ϕ_R is the known reaction plane angle (e.g. from the FTPC if we are using TPC data)**

  – **The second method is a true two particle correlation (many details left out)**

- **Under certain assumptions $b_1 = v_1$**

  – **Note that a 'normal' v_1 measurement for pions in a Au-Au reaction has an intrinsic symmetry that suggests weighting by sign(η)**

  – **Don't do this. We are looking for charge flow that goes up/down so without weighting the sum the 'normal' v_1 will cancel out. This assumes symmetric η acceptance.**

- **The signal is very small … so Voloshin proposed a very clever signal**

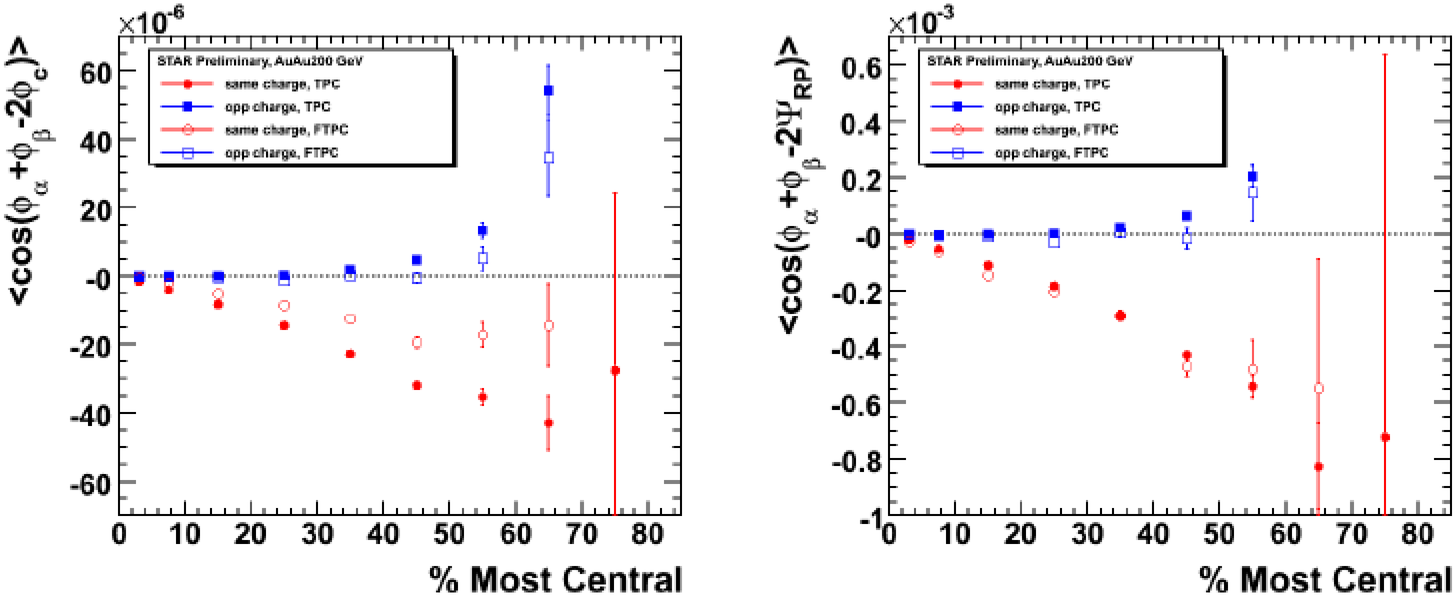
  – $\left\langle \cos(\phi_i - \phi_k)\ \cos(\phi_j - \phi_k) - \sin(\phi_i - \phi_k)\ \sin(\phi_j - \phi_k) \right\rangle = (b_1^2 - a_1^2)\, \mathrm{v}_2$

  – **Measure $(b_1^2 - a_1^2) * v_2$ because v_2 is large and it helps measure the parity non-conserving signal, a_1, while preserving reasonable statistical errors.**

  – **The observable $(b_1^2 - a_1^2) * v_2$ is a good way to measure charge sensitive flow because $(b_1^2 - a_1^2) * v_2 \Rightarrow a_1^2 * v_2$**

  – **If** $\mathrm{b}_\mathrm{n}^2 = \left\langle \cos(n(\phi_i - \phi_j)) \right\rangle$ **then** $a_1^2\, \mathrm{v}_2 \approx \left\langle \cos(\phi_i + \phi_j - 2\phi_k) \right\rangle$

Voloshin et al. see a signal



(a) (b) Voloshin, QM08 Poster

FIG. 1: (a) Comparison of correlations obtained using third particle in the main TPC and Forward TPCs. (b) The results after normalization to the flow of the third particle.

- **A signal appears to be present independent of how you determine the reaction plane.**
  - **It has been seen in several different collision systems and with several different estimates of Ψ_R**
- **Normally would assume that ++, -- have equal and opposite in sign to +-**
  - **Kharzeev suggests 'bubble' on edge of collision zone and one side absorbed**

A profound observation

- This would be a very significant discover if it is real
- Is it due to parity violation or something else?
  – Resonances?
  – Acceptance effects (aka dead sector in the TPC)
- Voloshin et al. have submitted a 'paper proposal' to STAR whereby they have found a reasonably large signal for the flow of positive particles vs negative particles (++, --, not +-)
  – It has been stewing for a while because the +- signal was not understood
- In support of their case, they see the signal in Au-Au and Cu-Cu, as well as with several different ways to define the reaction plane angle

Philosophy of getting involved

- I thought I would try to take a completely independent look at the signal to see if I can find it … and if it exists, can I test it .vs. my own unique view of the systematic errors in the STAR TPC

- Learn a little bit about flow analysis …
  – I've never done it before so I'm a complete neophyte

- Original Goal: reproduce the signal with full PID (i.e. no electrons)
  – The parity violating signal should affect quarks and not leptons
  – Previous results were for all particles in an event and did not include PID
  – Paul Sorensen said "If you are so smart, why don't you do it?"

- I eventually achieved that goal but I learned a great deal while making the journey because it allowed me to:

  'look under the hood' of the car and see how it works.

Method 1:

- JT code : produces a summary output. Output of this step goes to analysis code written by Vasily

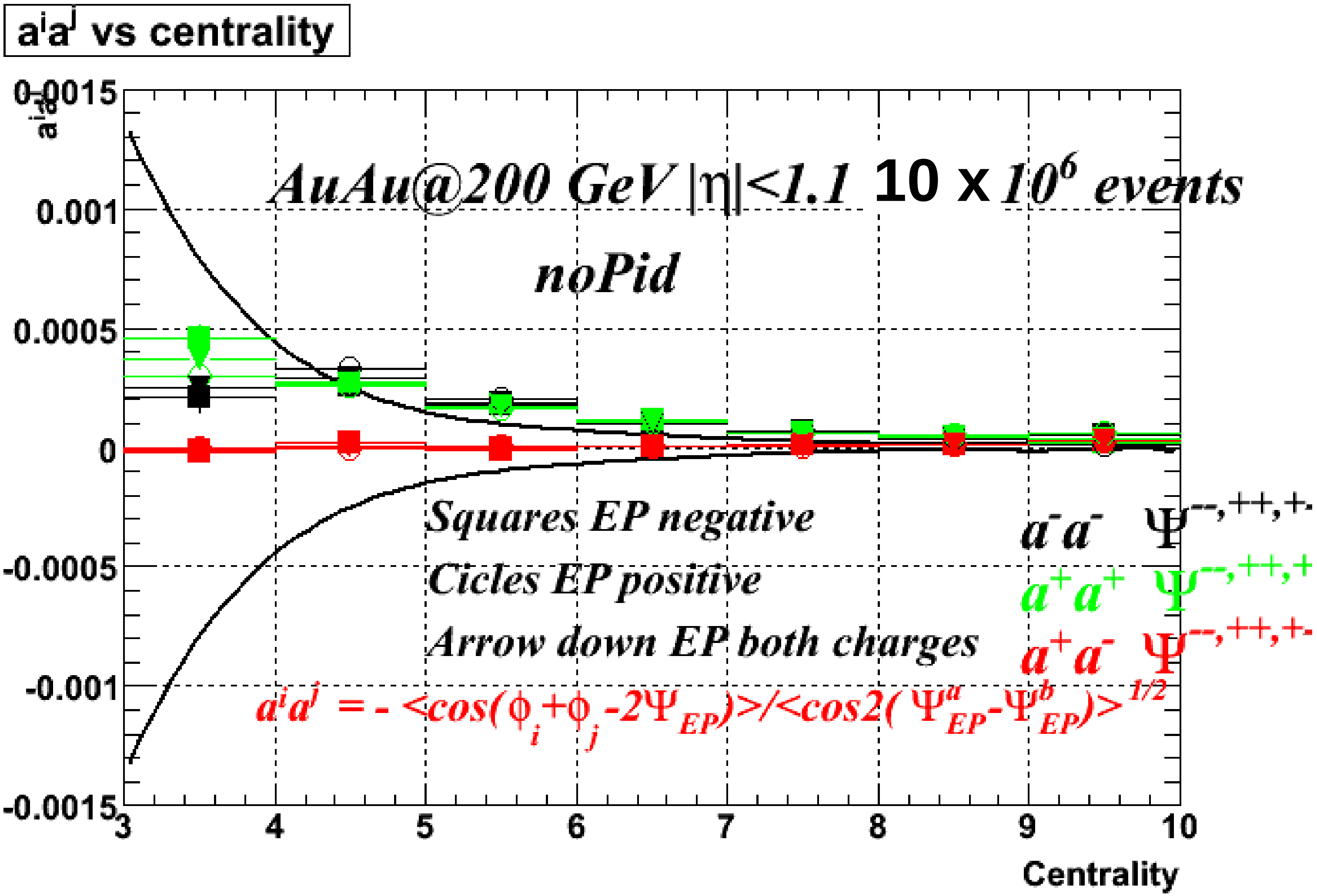
- Vasily’s code : 3 particle correlation study using Jim’s
- output files : ~2-3 hours + few minutes for correlation
- plots

- Statistics analysed: 14 M AuAu 200 GeV, Run 4

|Zvertex| < 30.   dca < 3.0   0.15 < Pt < 2.0

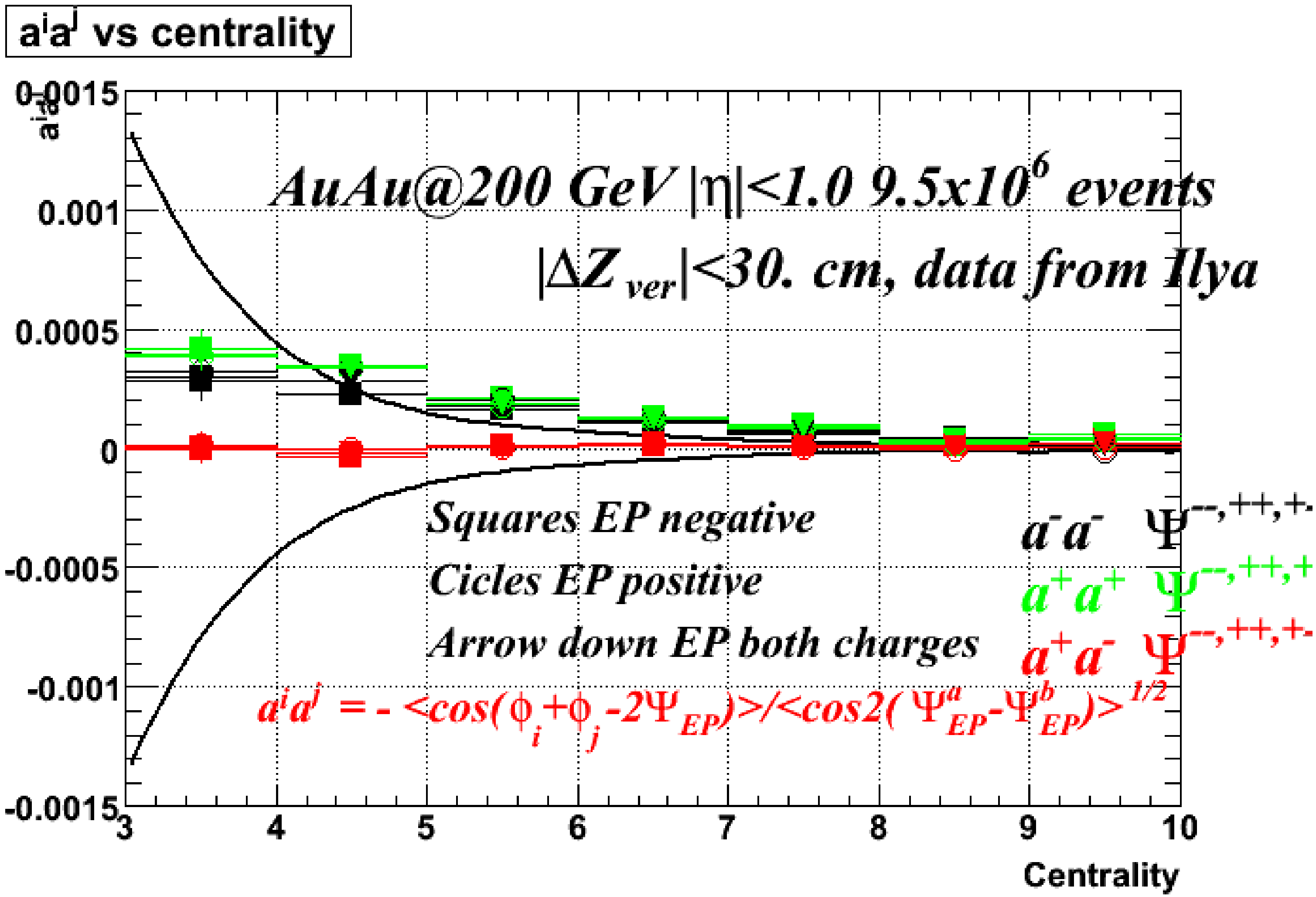
15 < Nhits < 45   nHitPoints/nHitsPossible>0.52

Run 4, AuAu 200 GeV, 9.5 M (Vasily & JT)



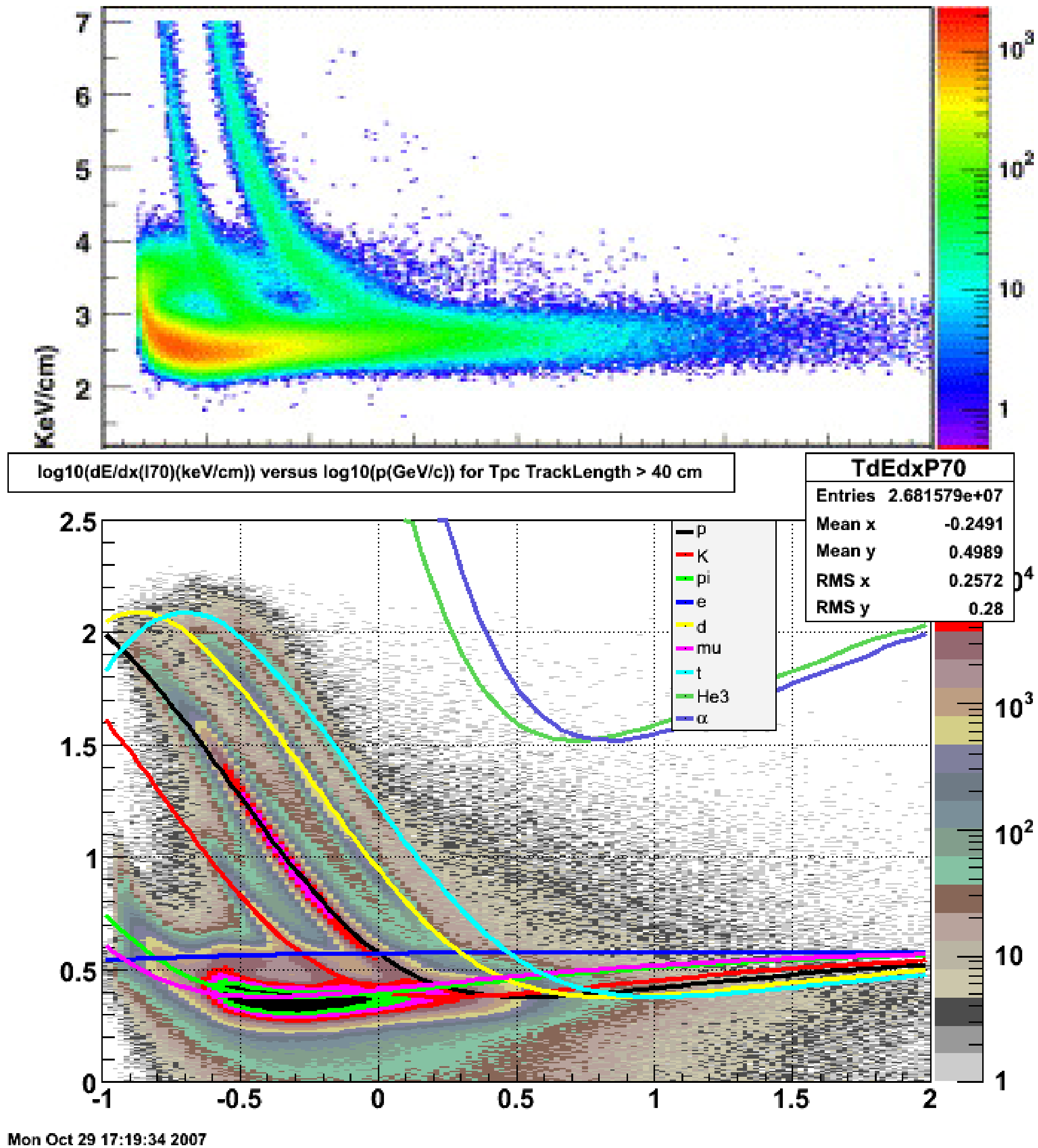
Vasily's code produces similar results to Voloshin et al.
Note: Phi weights NOT applied to these data

Run 4, AuAu 200 GeV, 9.5 M (Ilya & Sergei)

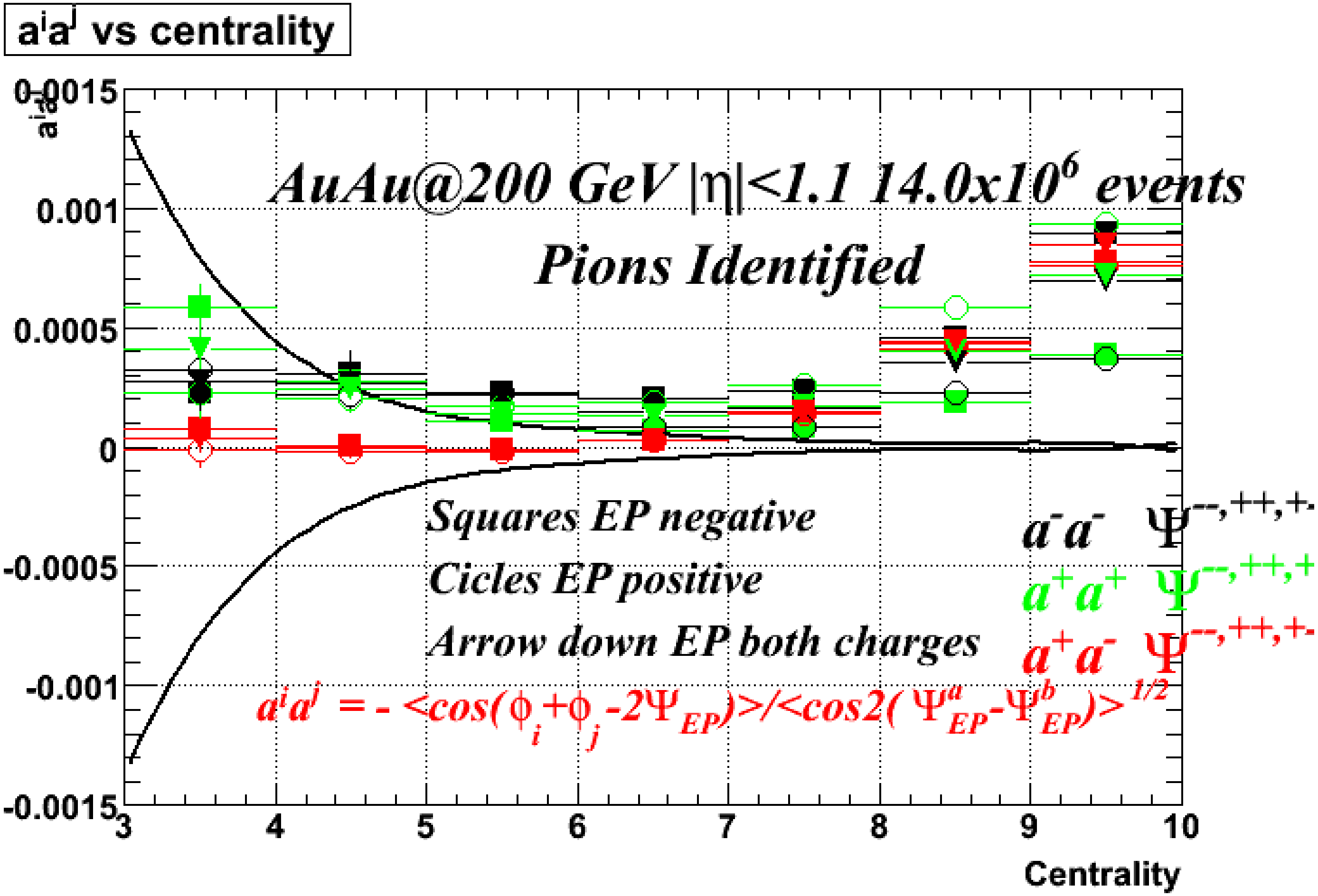


The signal as reported by Voloshin et al.

Now turn on PID?   (e.g. Signal with pions)



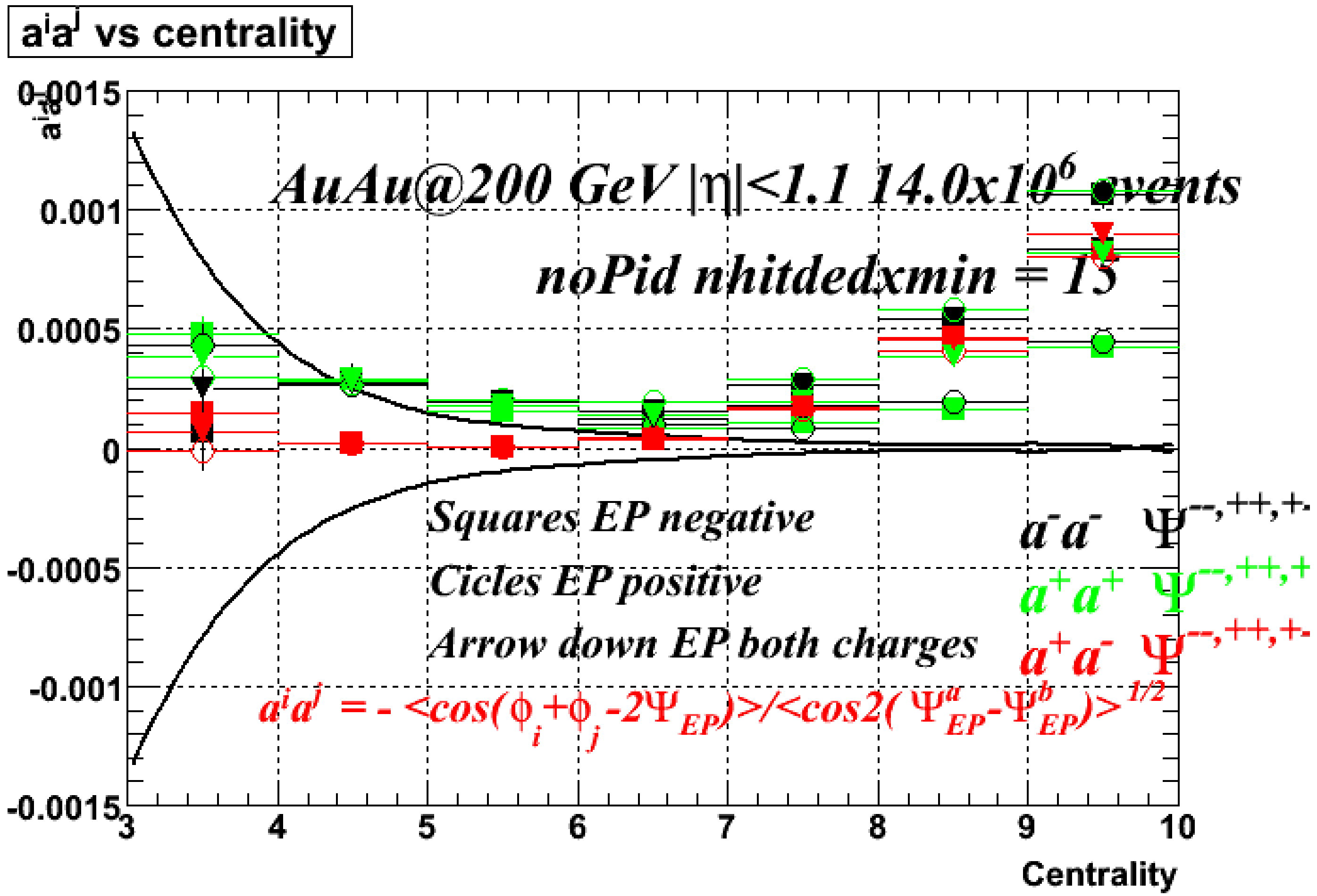
Run 4, AuAu 200 GeV, ~14M (with π ID)



First attempt at PID suggests that the $a_1$2 v2 signal is not unique to Parity Violation**
Note: Phi weights not applied to these data

Run 4, AuAu 200 GeV, ~14M

nHitDedxMin = 15



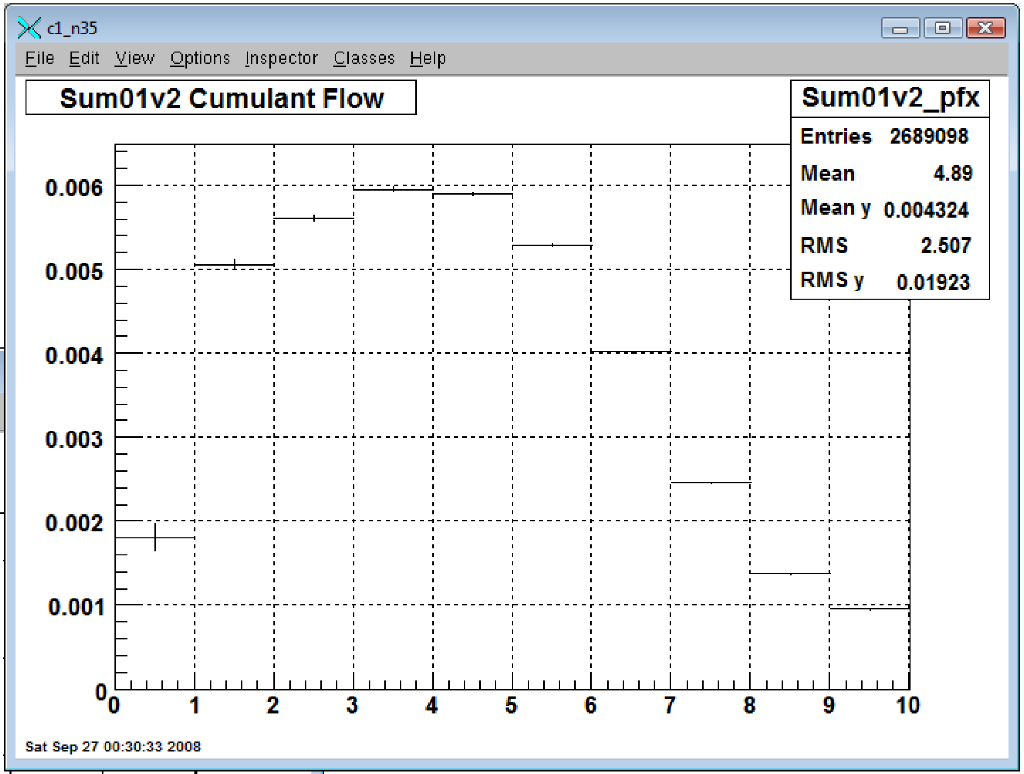
nHitsDedx story suggests P isn't a unique signal

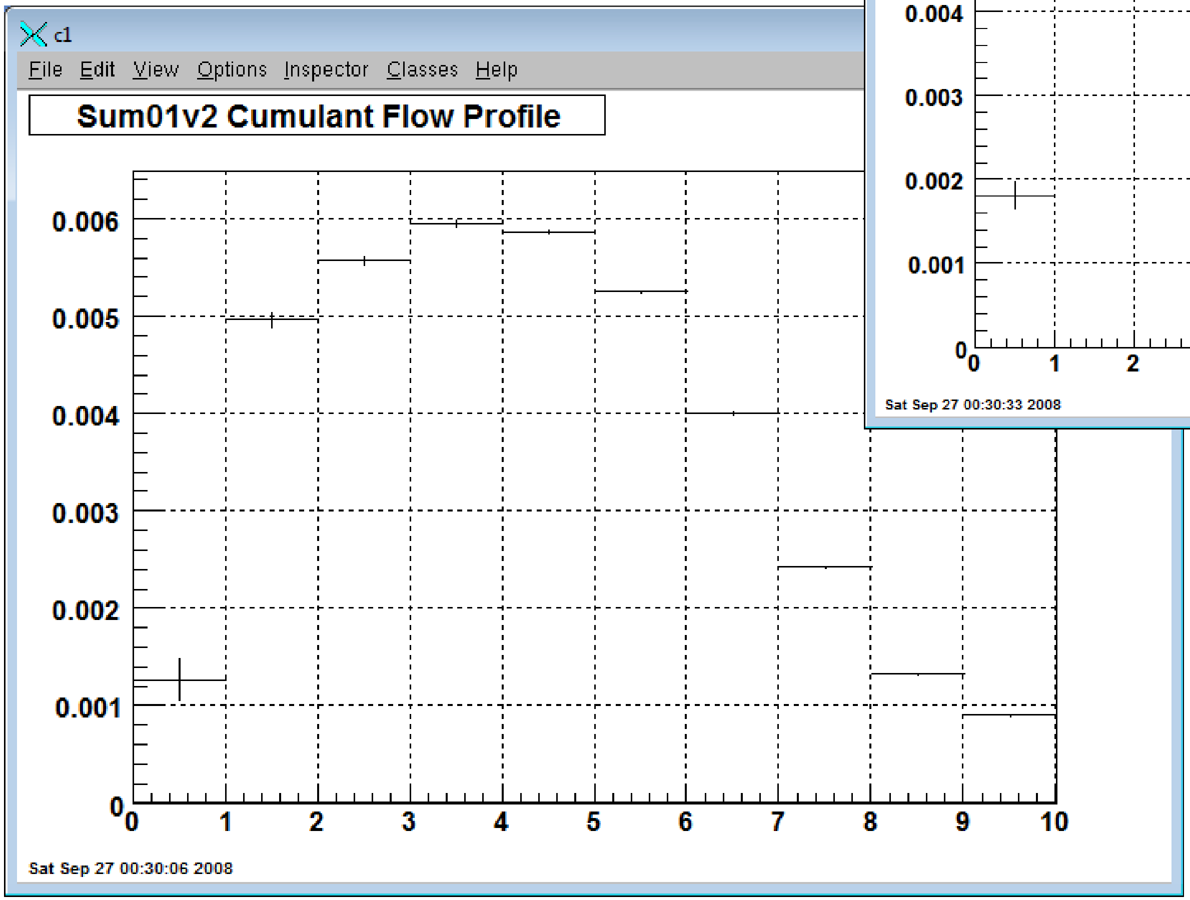
- In order to select an identified particle, you have to request a track with a minimum number of calibrated clusters for dEdx measurements. Not all clusters that lie on a track are good for dE/dx measurements because the gain changes near the ends of pad rows and/or the gain changes near the endcaps and thus cannot be calibrated.
- nHitsDedx selects the number of dEdx clusters on a track. The maximum possible is 45, with a mean number of hits of about 30, and so it is common to require that at least 15 of these are good dEdx hits before declaring that a track has a good particle ID. (This is different than > nHitsFit which merely counts the number of hits used in fitting a track.)
- We found signals just by requiring nHitsDedx > 15. We did not have to go to step 2 and select a particle type... just turn on the nHitsDeDx cut without selecting a particle type and this will happen.

If you try to do any sort of particle ID, you have to turn on this cut and the act of employing this cut appears to create a signal.

What are the effects of phi weights and …

Without acceptance corrections ⇒



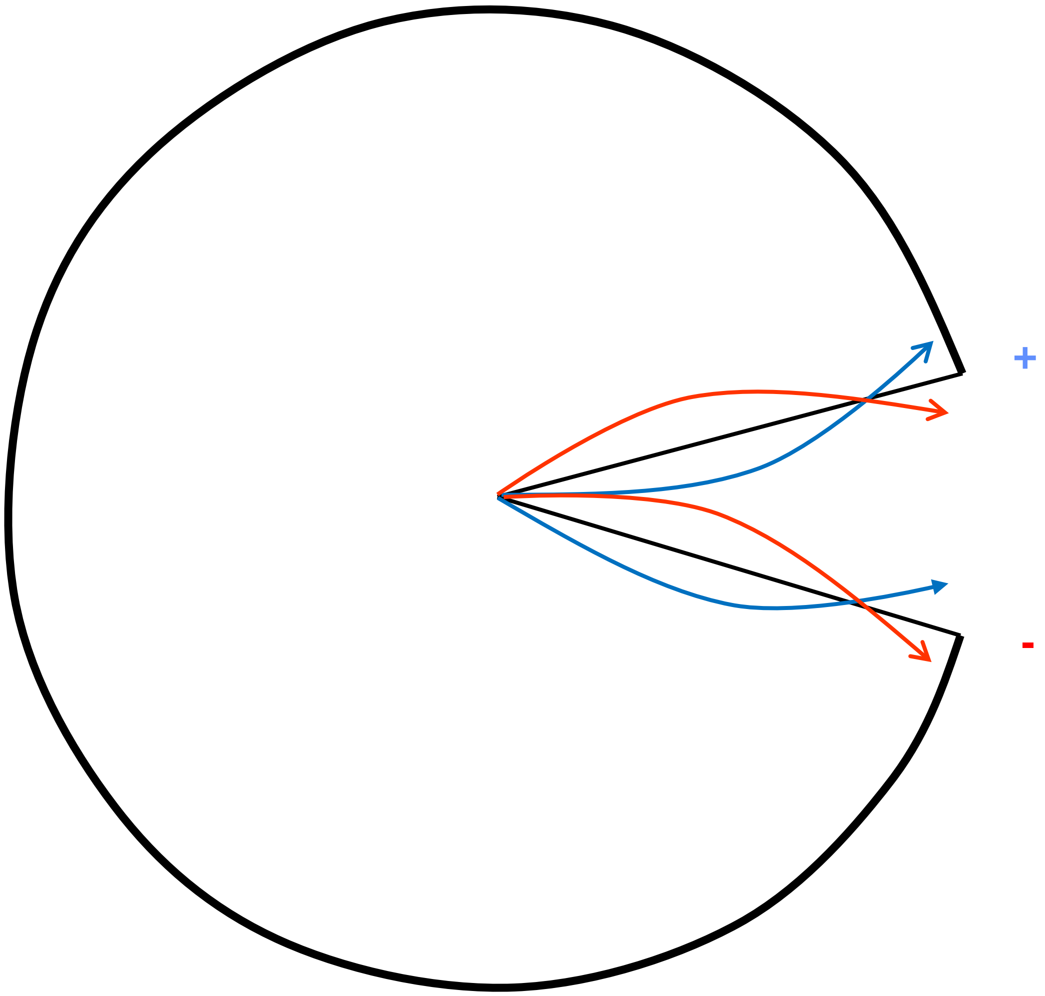


⇐ with all corrections

Removing acceptance corrections and multi-particle correlations not necessary … no effect on v_2

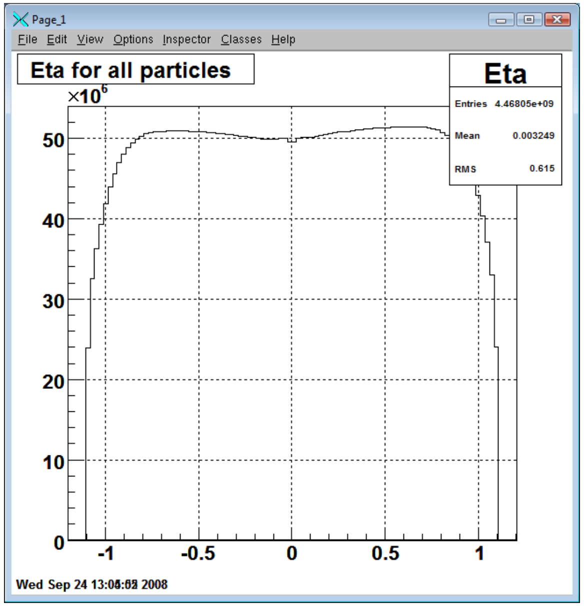
Non-Hermetic Acceptance …

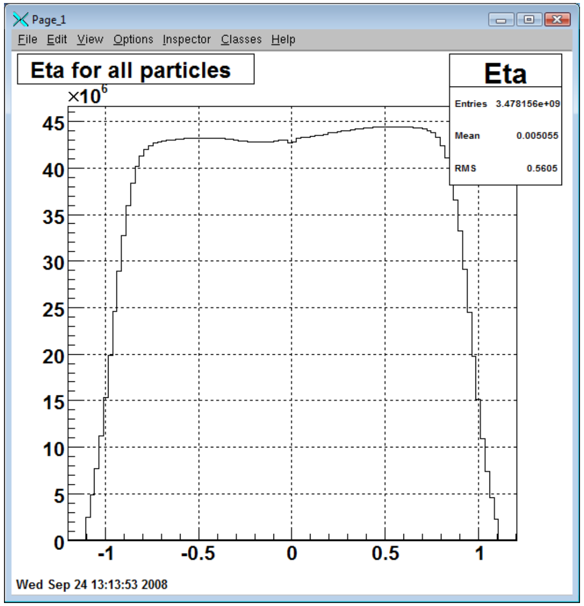
- **Do ϕ weight corrections work well enough to handle the case of a small parity violating signal?**
- **The technology is robust in principle but not really tested by v_2 studies**
- **Note ϕ weight corrections only had small impact on parity signal for data selected without PID**

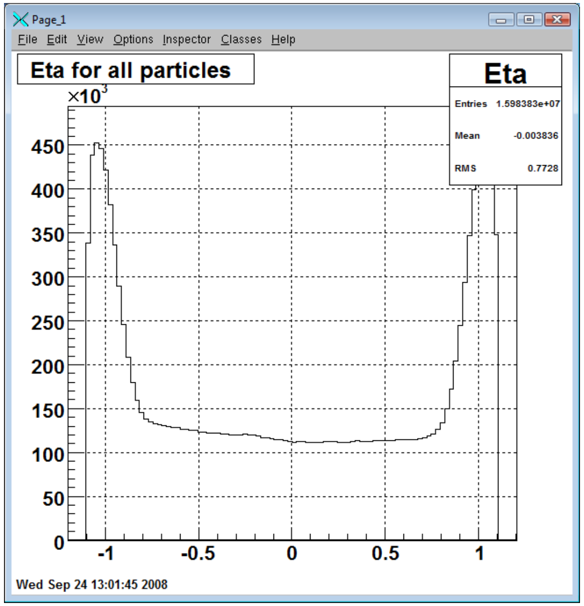


… can lead to false signals

What does nHitsDedx do? It is a fiducial cut.







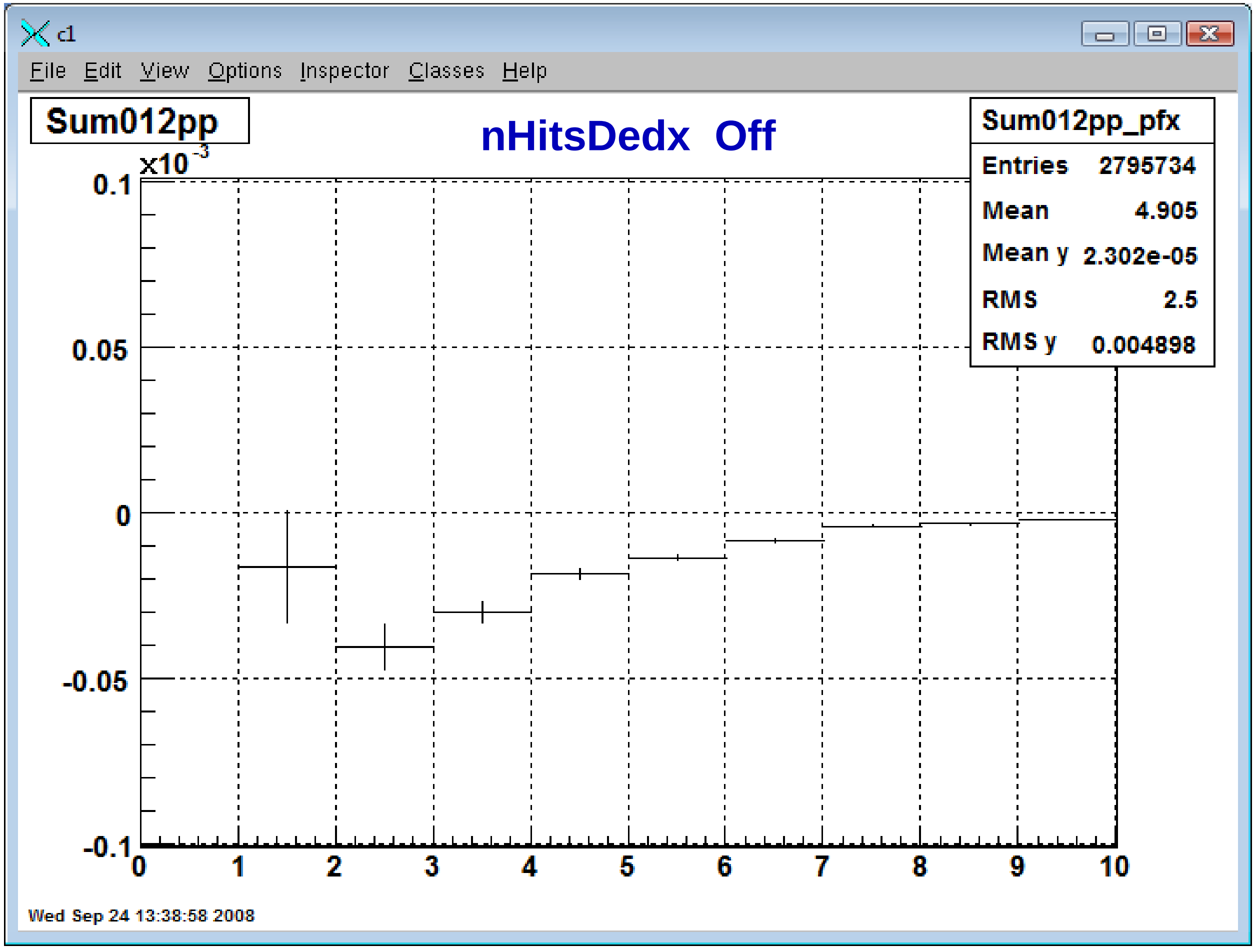
nHitsDedx off

nHitsDedxMin = 15

nHitsDedx rejected tracks

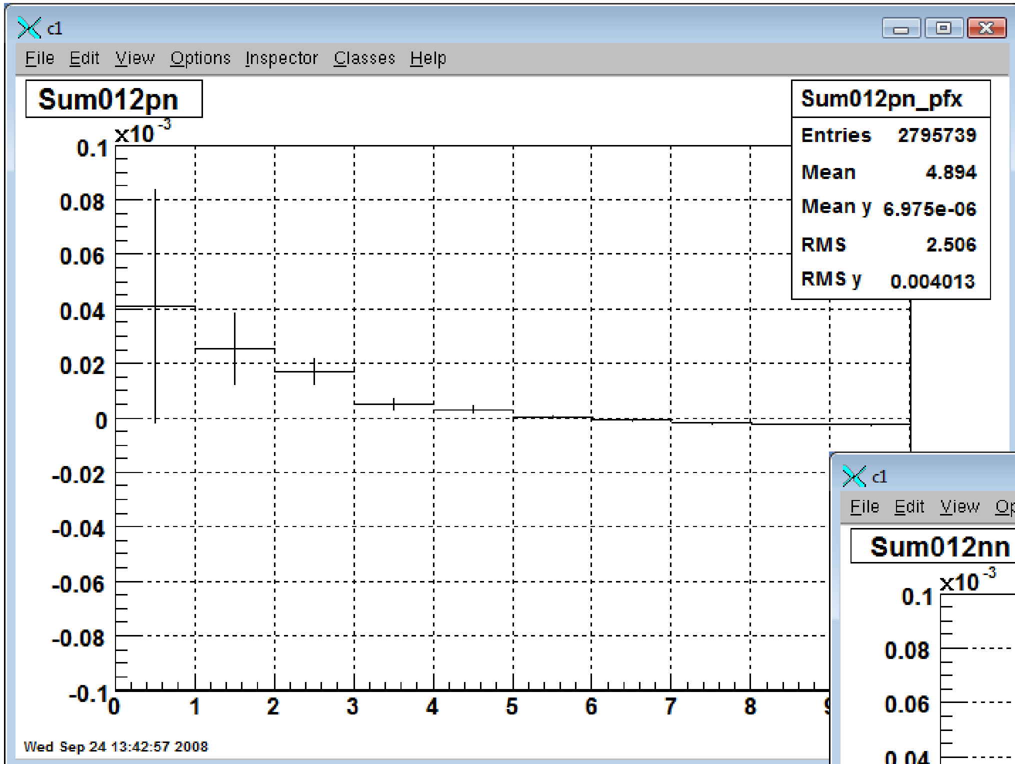
nHitsDedx is a well defined change in the acceptance of the TPC to identify higher quality tracks for PID analysis

A different approach: 3 Particle Cumulant results

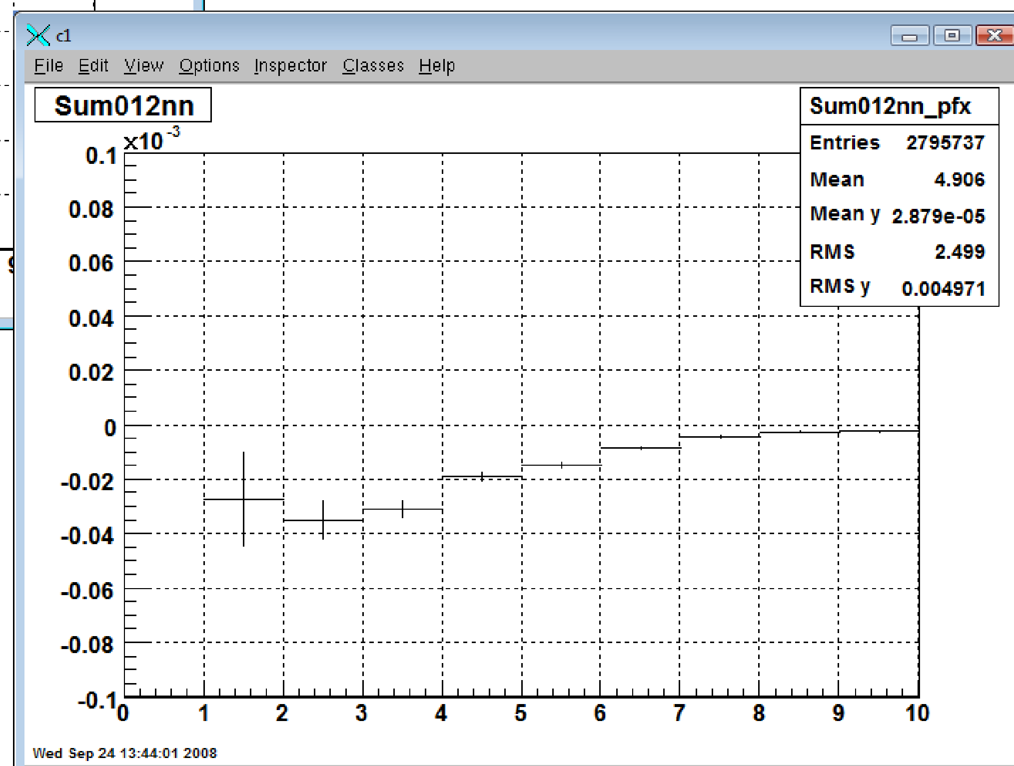


$$a_1^2\, v_2 = \left\langle \cos(\phi_i + \phi_j - 2\phi_k) \right\rangle - \left\langle \cos(\phi_i + \phi_j) \right\rangle \left\langle \cos(-2\phi_k) \right\rangle - \left\langle \cos(\phi_i - 2\phi_k) \right\rangle \left\langle \cos(\phi_j) \right\rangle - \left\langle \cos(\phi_i) \right\rangle \left\langle \cos(\phi_j - 2\phi_k) \right\rangle + 2 \left\langle \cos(\phi_i) \right\rangle \left\langle \cos(\phi_j) \right\rangle \left\langle \cos(-2\phi_k) \right\rangle$$

3 Particle Cumulant results



nHitsDedx Off



Very similar results to Vasily and Illya's analyses

Similar nHitsDedx behaviour as before …

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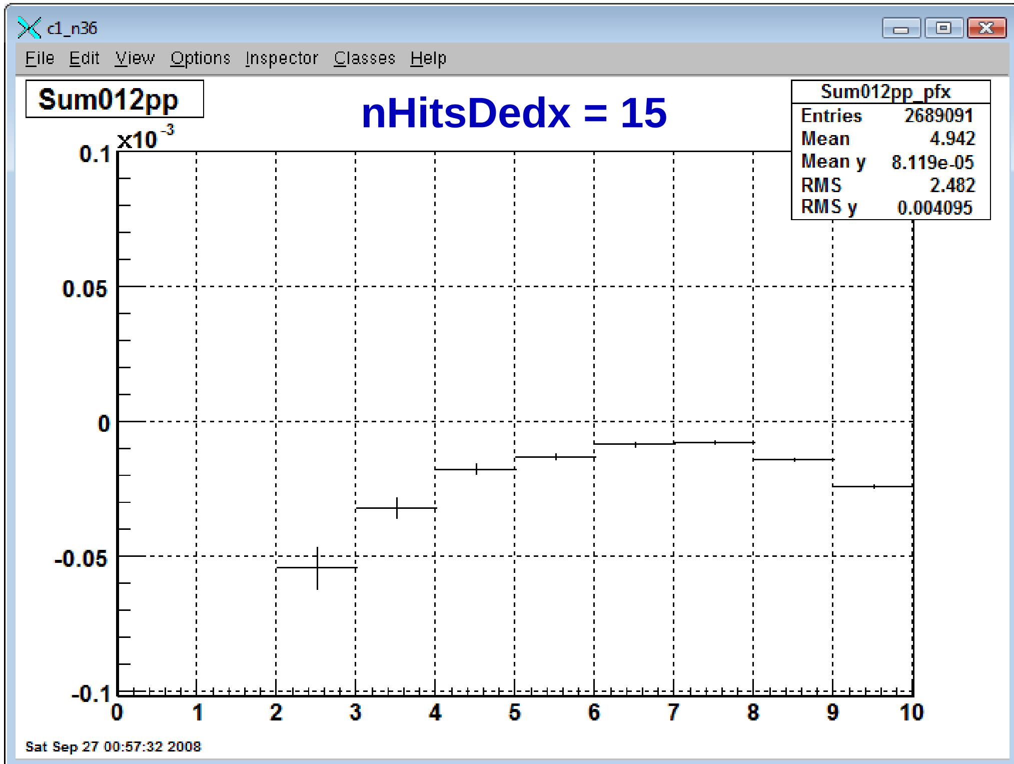
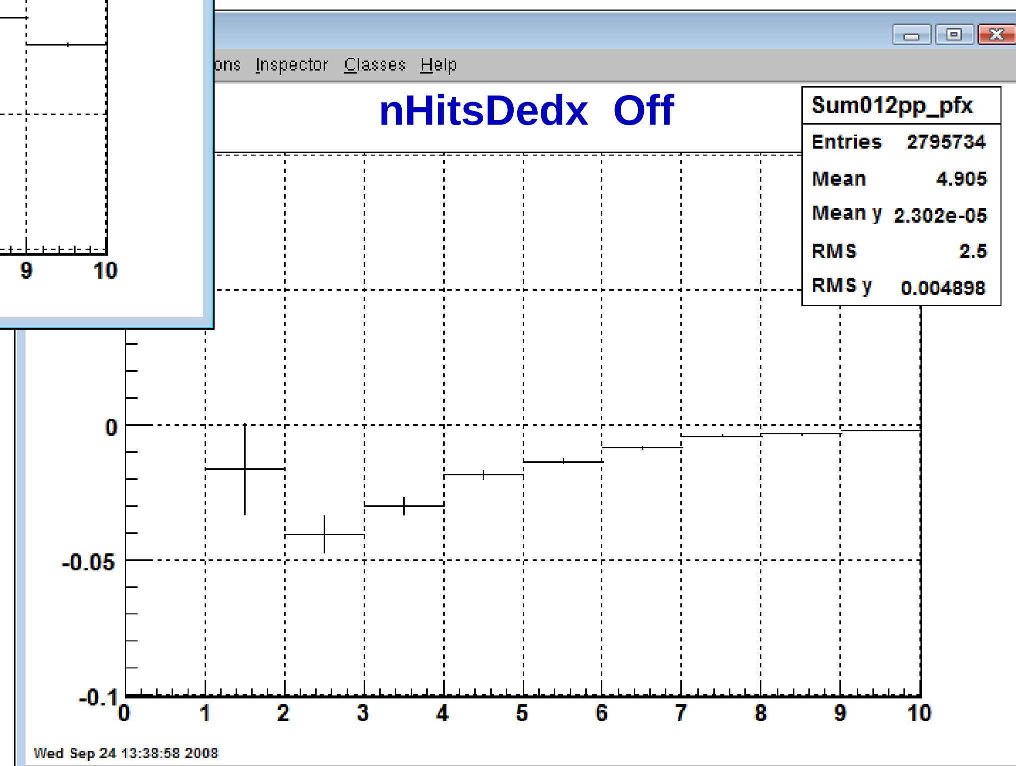
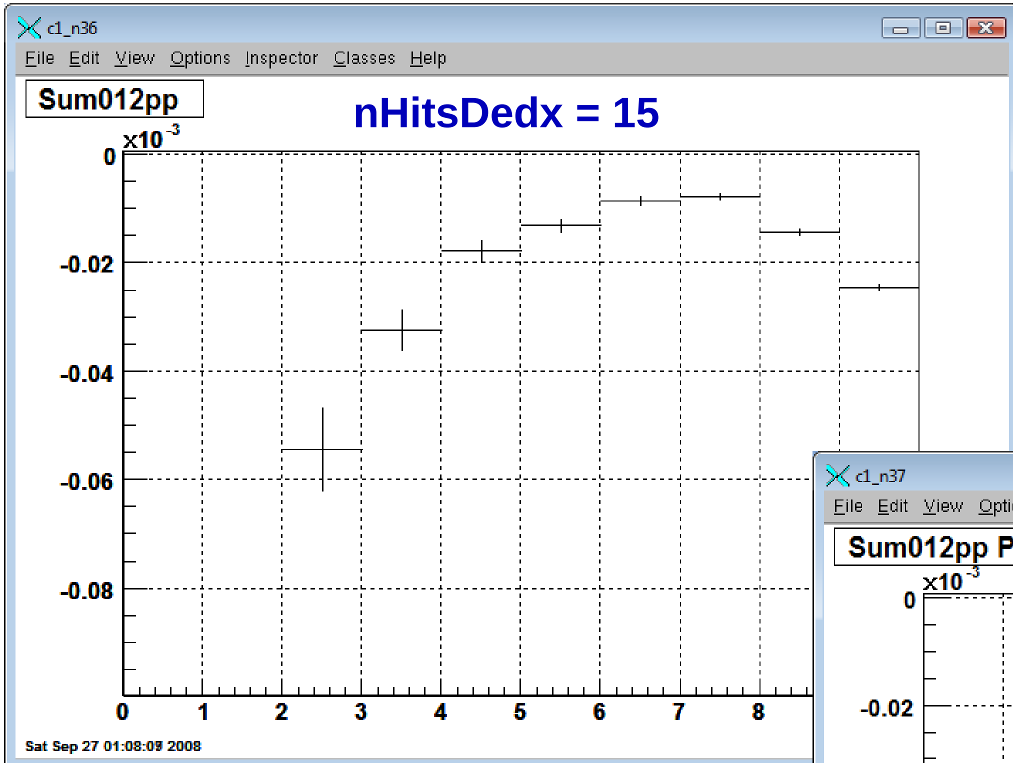


$$a_1^2 \, v_2 = \left\langle \cos(\phi_i + \phi_j - 2\phi_k) \right\rangle$$

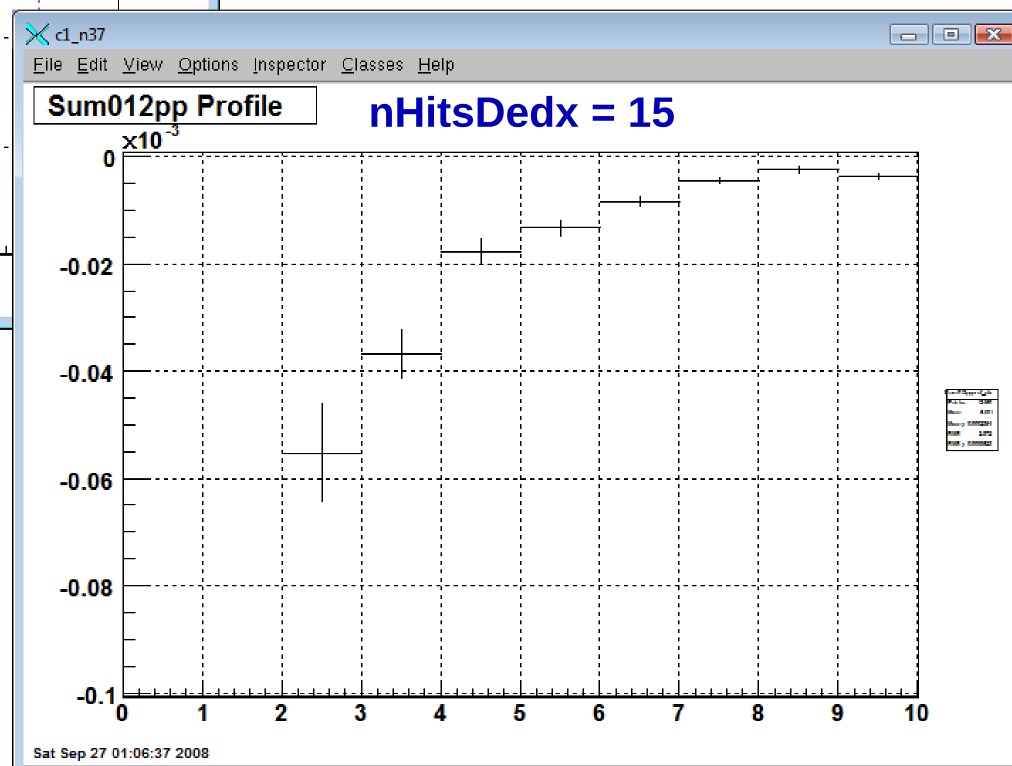


Anomalous result is robust across techniques … but now we have an additional tool that is easy to turn on and off

Add the cross terms and … a very pretty result

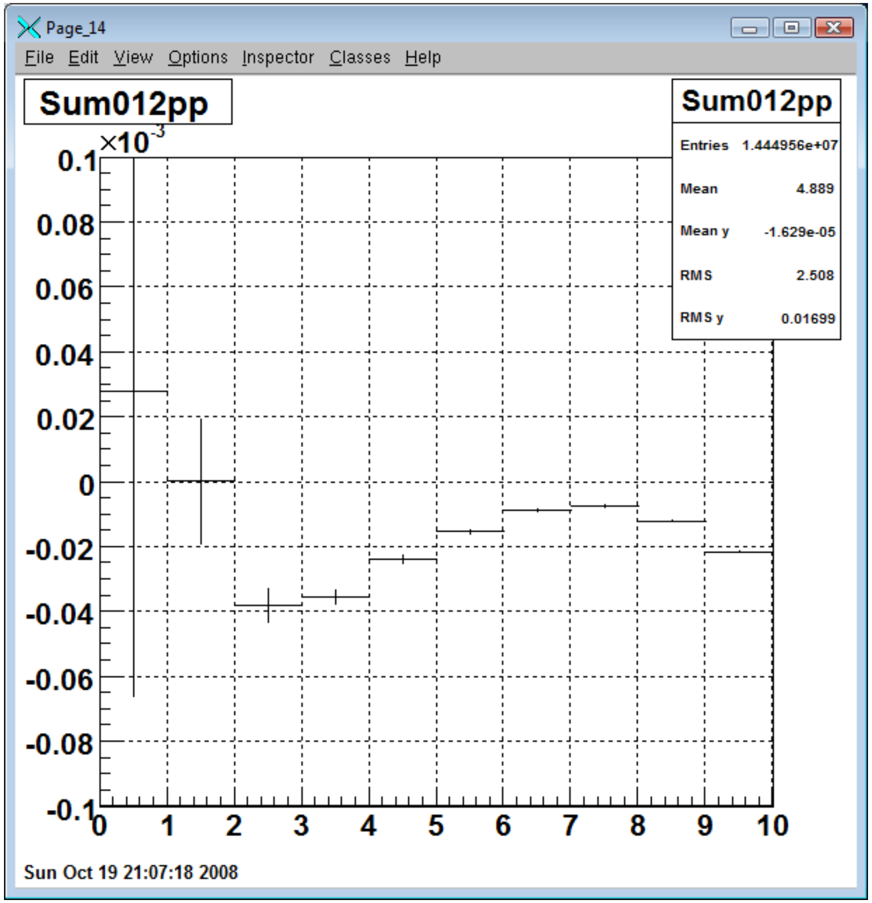


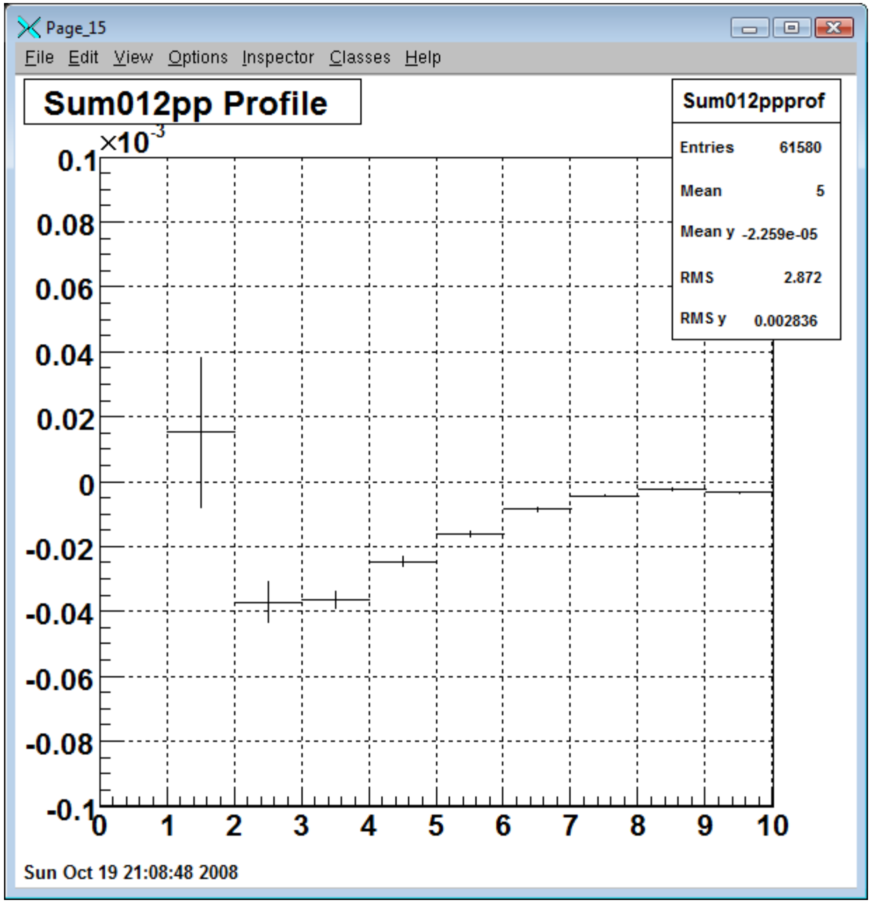
- **Full cumulant includes lower order corrections for two particle correlations and acceptance effects. Seems to work very smoothly.**



- **Full cumulant corrections are required for small signals … not necessarily required for large signals (e.g. v_2)**

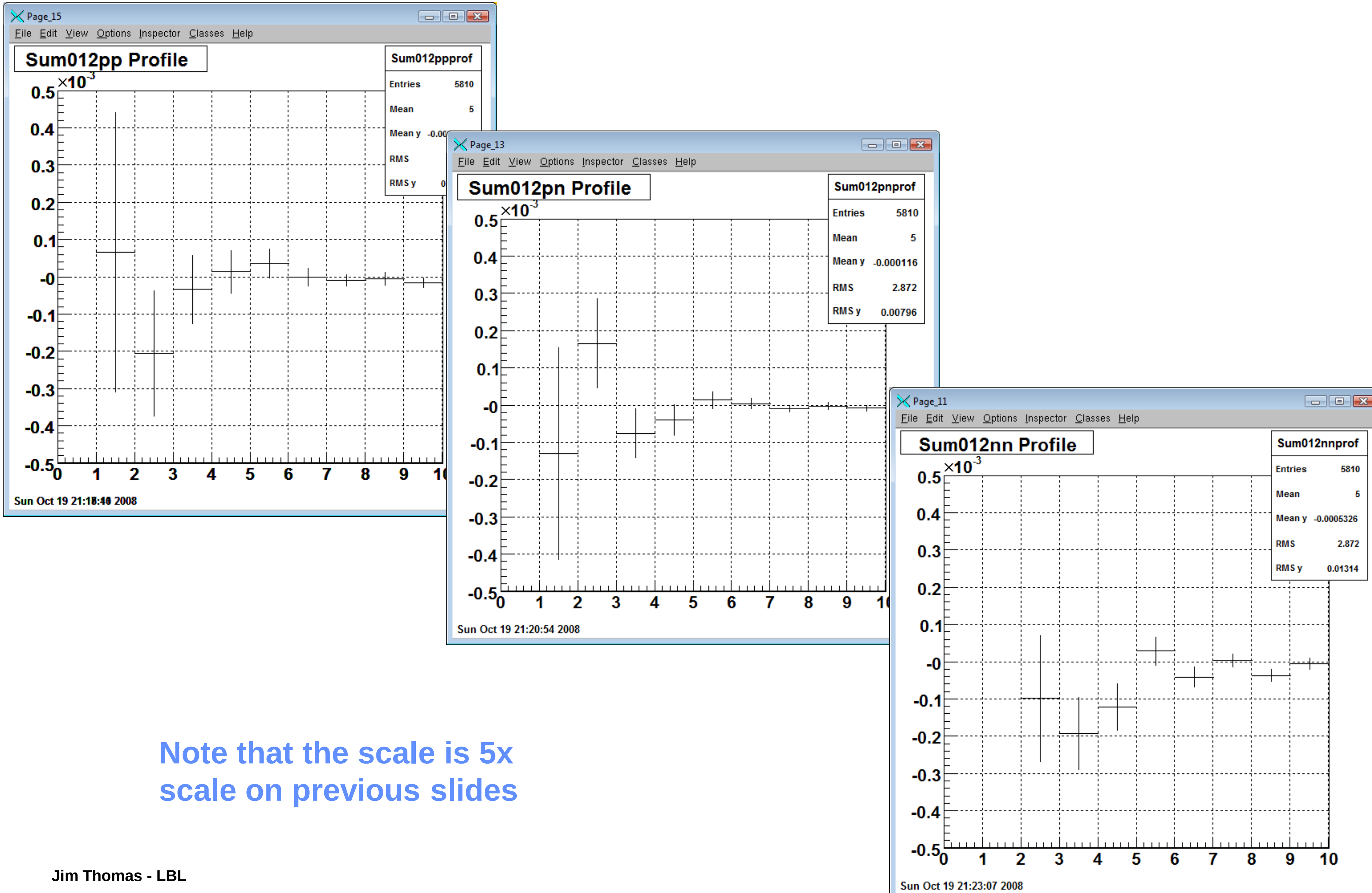
The next step is PID (the original goal)





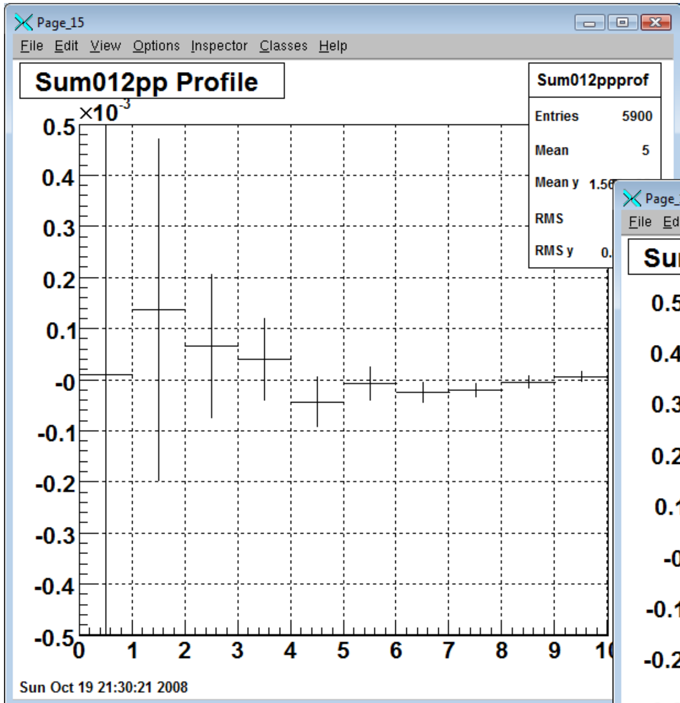
Pions Identified and electrons rejected (nHitsDedx = 15)

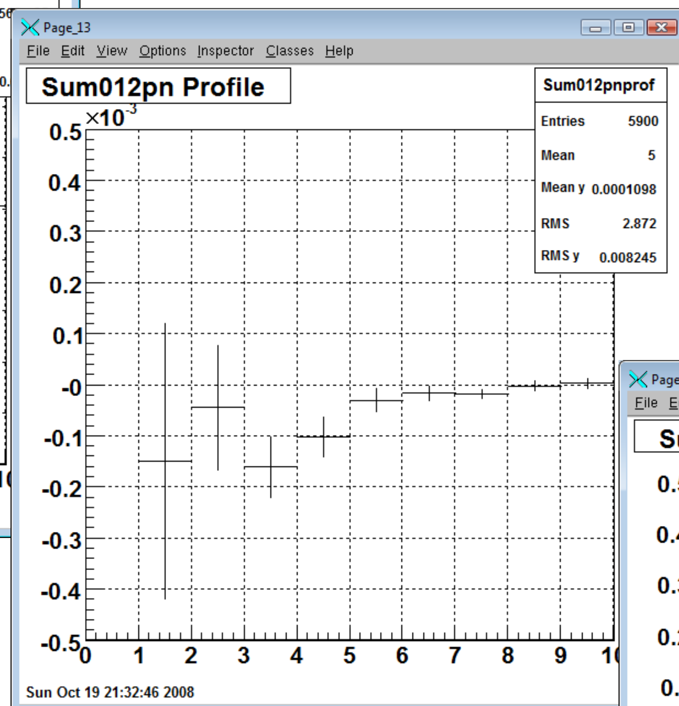
Identified Kaons (e & π rejected)

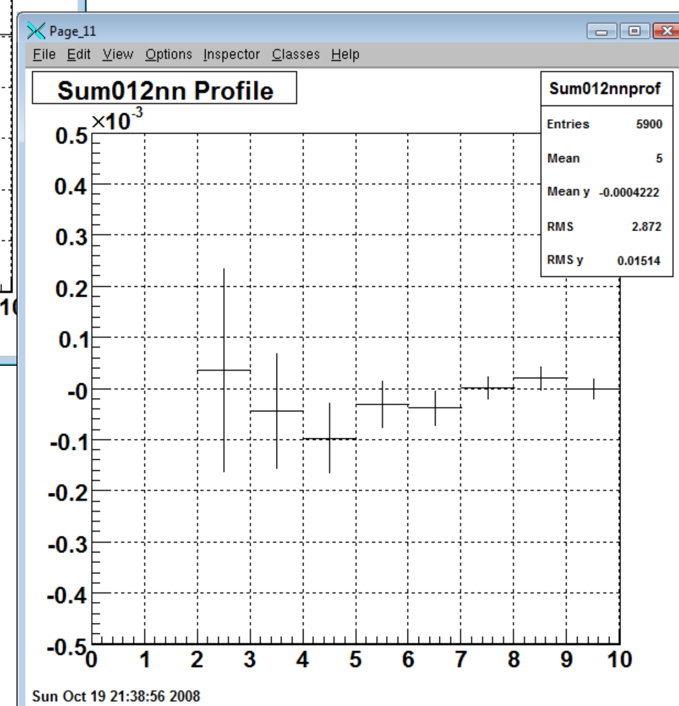


Note that the scale is 5x scale on previous slides

Identified Protons (e & π rejected)







Note that the scale is 5x

Conclusions

- There is a signal for $a_1^2 * v_2$ which is present in the Au-Au data
  - Several different groups and different techniques can find it
  - The question is: what is it?
- It may be the signature of parity violation in the strong interaction
  - This would be very profound and a wonderful discovery
- It may be the artifact of even more complex acceptance cuts
  - If the reaction plane is not perfectly randomized with respect to the detector, then simple acceptance effects can lead to a signal
  - It may be the result of other physics processes, resonances, etc.
- The $a_1^2 * v_2$ signal is not unique to parity violation
  - nHitsDedx is a quality cut that creates a false signal
  - However, removing the lower order multi-particle correlations does a very pretty job of cleaning up the effects of the nHitsDedx fiducial cut … and didn't remove the nominal signal. Very nice result.
- The signal is present for identified pions (with e^- rejected)
  - Identified kaons and protons show interesting systematics, too.