SEARCH FOR LOCAL STRONG PARITY VIOLATION IN STAR USING MULTIPLE OBSERVABLES

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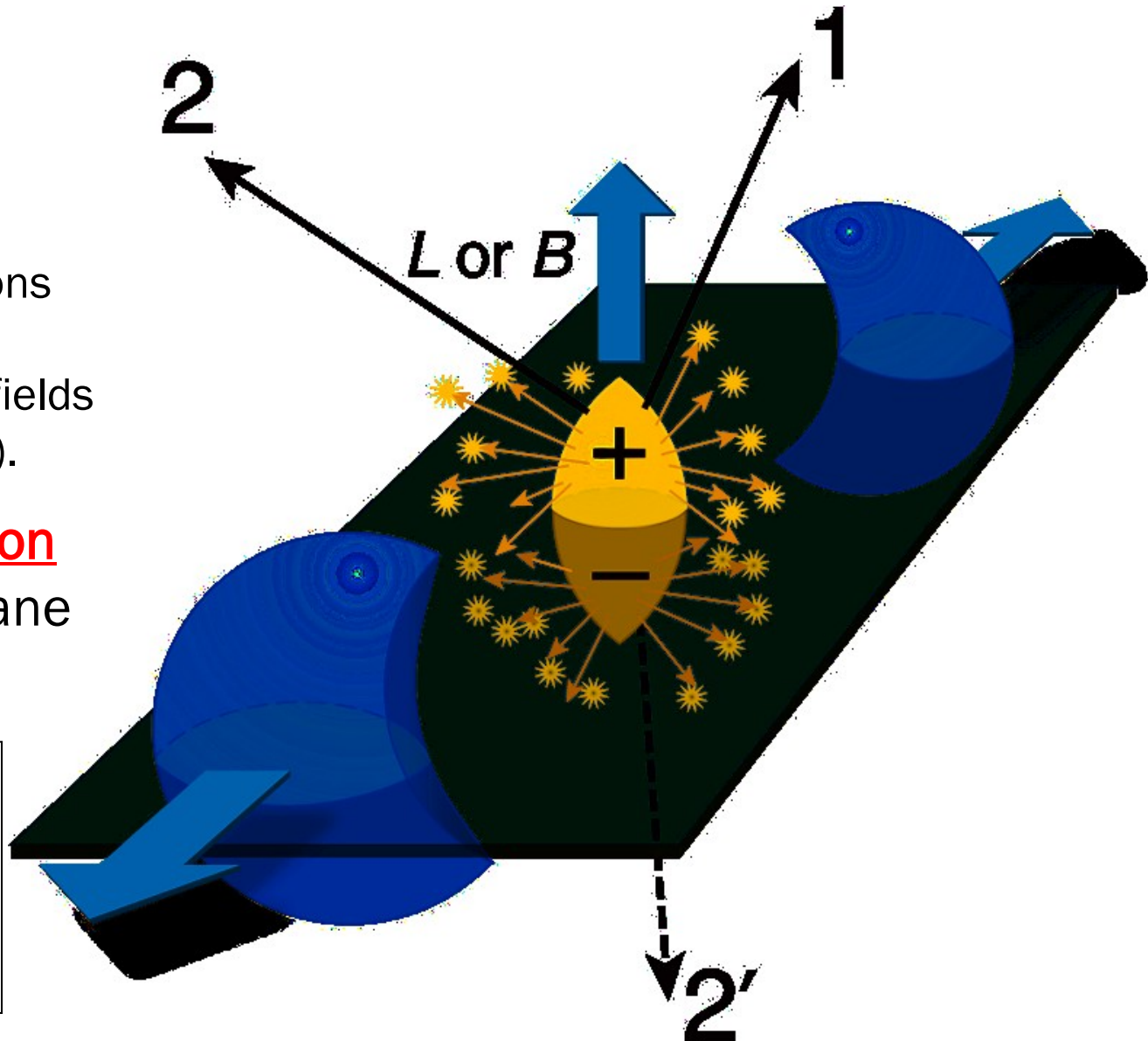
THE CHIRAL MAGNETIC EFFECT (CME)

2 Ingredients

1. QCD vacuum transitions (P-odd)
2. Very large magnetic fields (~1000 trillion Tesla!).

= Charge Separation wrt the reaction-plane



- D. Kharzeev. Phys. Lett. B **633**:260 (2006).
- D. Kharzeev, L. McLerran, H. Warringa. Nucl. Phys. A **803**:227 (2008).

THREE POINT CORRELATION

$$\left\langle \cos\left(\phi_a + \phi_b - 2\Psi_{EP}\right)\right\rangle$$

S.A. Voloshin. Phys. Rev. C., **70**:057901 (2004)

$$= \left\langle \cos\left(\phi_a - \Psi_{EP}\right)\cos\left(\phi_b - \Psi_{EP}\right)\right\rangle - \left\langle \sin\left(\phi_a - \Psi_{EP}\right)\sin\left(\phi_b - \Psi_{EP}\right)\right\rangle$$

$$= v_1^a v_1^b + B_{In} - a_1^a a_1^b - B_{Out}$$

- Directed flow part negligible for symmetric eta range.
- Contribution from flow fluctuations expected to be ~ 10^{-5}. With fluctuating initial conditions v_1^2-a_1^2 ~ 10^{-4}. But ss=os in the model.

D. Teaney & L. Yan. arXiv:1010.1876v1

Sensitive to out-plane charge separation fluctuations

P-even backgrounds.
These may or may not cancel.

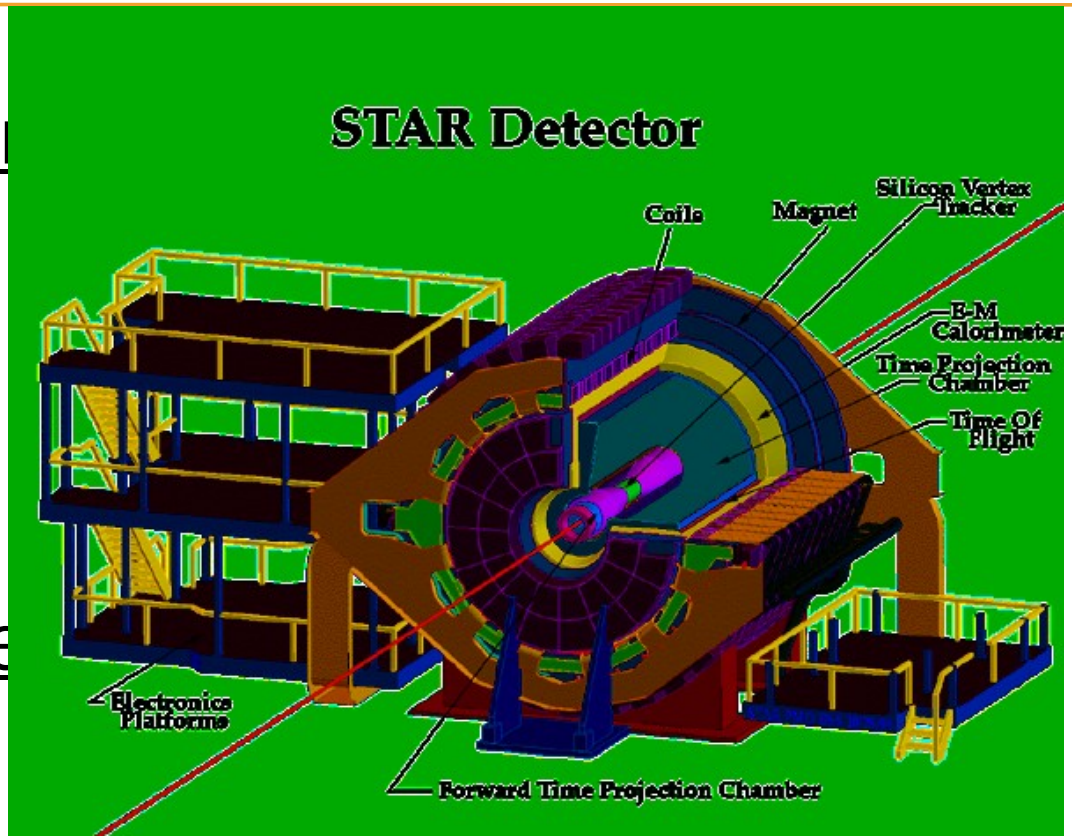
DATA SELECTION

AuAu MinBias Collisio

√s = **200 GeV** – 57 M events
62.4 GeV – 2.4 M events
39 GeV – 8M events
11.5 GeV – 10M events
7.7 GeV -- 4M events

Track Fiducial Range

0.15 < pt < 2.0 GeV/c
|η| < 1.0



Tracking done with the Time Projection Chamber
Triggering done with the Zero Degree Calorimeter

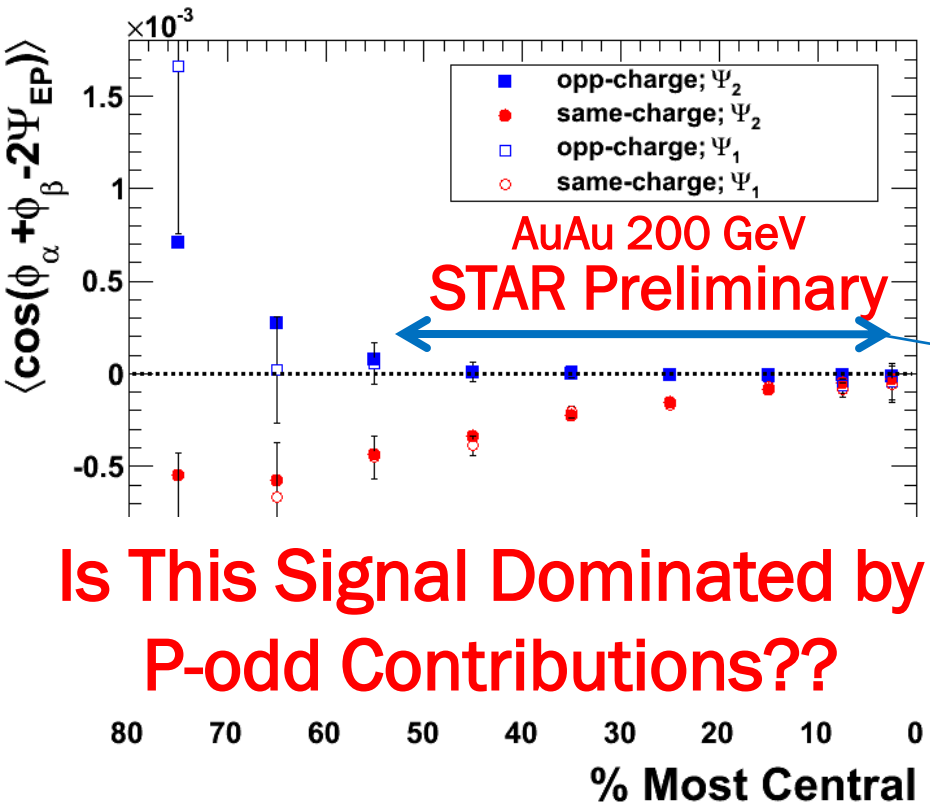
THE CENTRAL QUESTIONS

Do we observe this effect in heavy-ion collisions?

STAR
Phys. Rev. Lett.
103: 251601
(2009)

Consistent with the idea of charge separation across the reaction plane

Ψ_1 = ZDC-SMD EP
(1st order)
Ψ_2 = TPC EP
(2nd order)

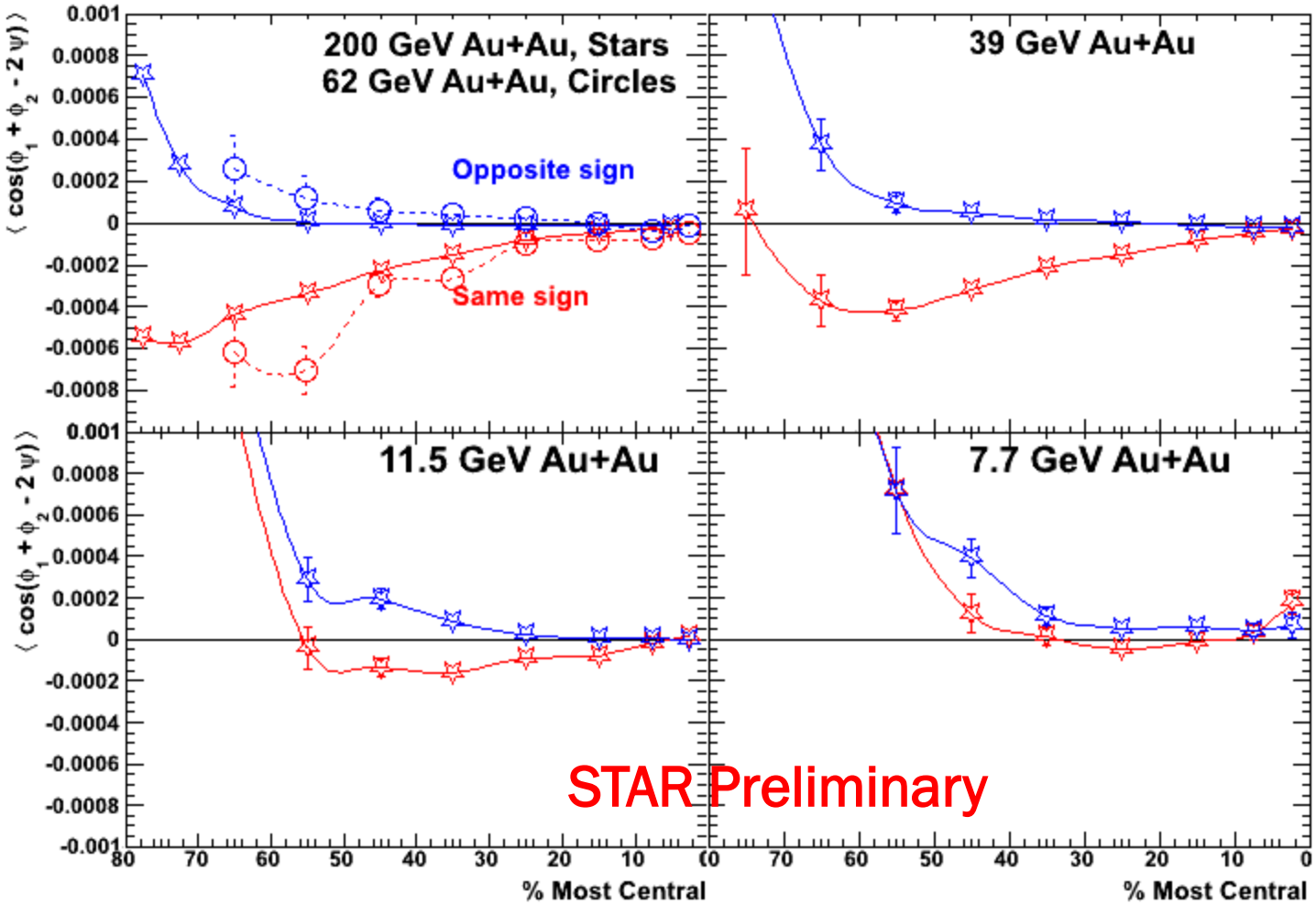


Signal is likely a genuine correlation wrt the reaction plane!

Are opposite charge correlations suppressed by medium interactions?

Is This Signal Dominated by P-odd Contributions??

ENERGY DEPENDENCE



An Evolution
Mostly of Same-charge Correlations

As the Energy decreases:
1.) The B field decreases but lasts longer.
2.) Chiral symmetry may cease to be restored.

The difference between same-charge and opposite charge correlations is decreasing with decreasing energy.

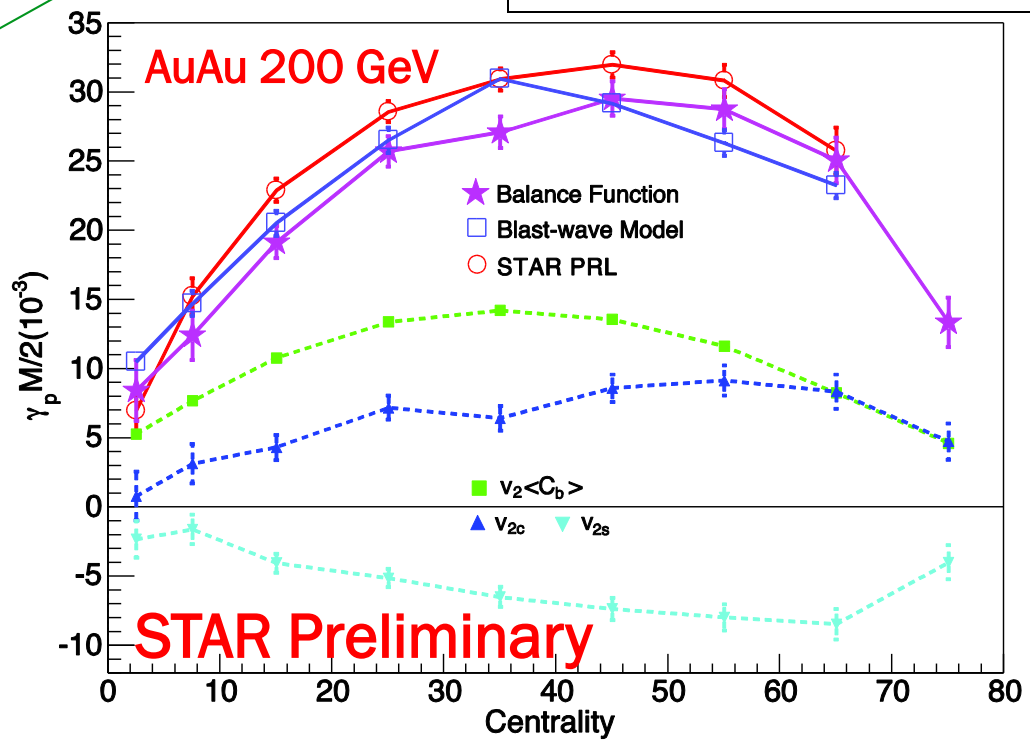
BALANCE FUNCTION APPROACH

$$\gamma_p = \frac{1}{2}(2\gamma_{+-} - \gamma_{++} - \gamma_{--}) = \frac{2}{M}\left[v_2\langle c_b(\phi)\rangle + v_{2c} - v_{2s}\right]$$

Positive if more charge pairs are found in plane

Positive if charges are more correlated in-plane

Negative if charges are more correlated on the in plane side



Reaction plane dependent balance function is related to $\cos(\varphi_a+\varphi_b-2\psi)$.

A Blast-wave model can reproduce the observed difference between opposite and same charge correlations

Figure by Hui Wang. See Poster #381 for Details

A MODIFIED THREE POINT CORRELATOR

$$= \left\langle \cos\left(\phi_a - \Psi_{EP}\right)\cos\left(\phi_b - \Psi_{EP}\right)\right\rangle - \left\langle \sin\left(\phi_a - \Psi_{EP}\right)\sin\left(\phi_b - \Psi_{EP}\right)\right\rangle$$

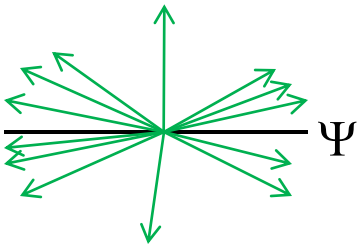
$$= \left\langle M_a S_a M_b S_b \right\rangle_{In-plane} - \left\langle M_a S_a M_b S_b \right\rangle_{Out-plane}$$

M = magnitude of cosine or sine
S = sign: ±1

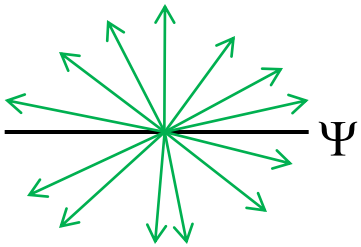
Reduction

Randomize the azimuthal angles of the particles while keeping them on the same side of the event-plane.

Before



After

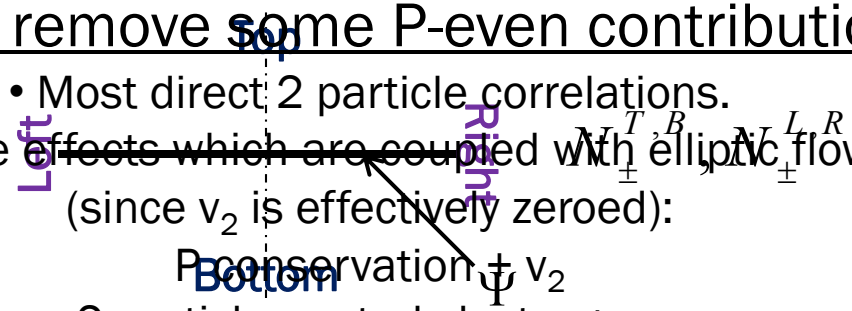


A Modulated Sign Correlation (MSC)

$$\rightarrow \left(\frac{2}{\pi}\right)^2 \left(\left\langle S_a S_b \right\rangle_{In-plane} - \left\langle S_a S_b \right\rangle_{Out-plane}\right)$$

This will remove some P-even contributions:

- Most direct 2 particle correlations.
- Some effects which are coupled with elliptic flow (since v_2 is effectively zeroed):
  - P conservation + v_2
  - 2 particle neutral cluster + v_2

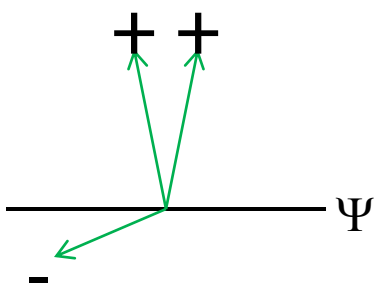


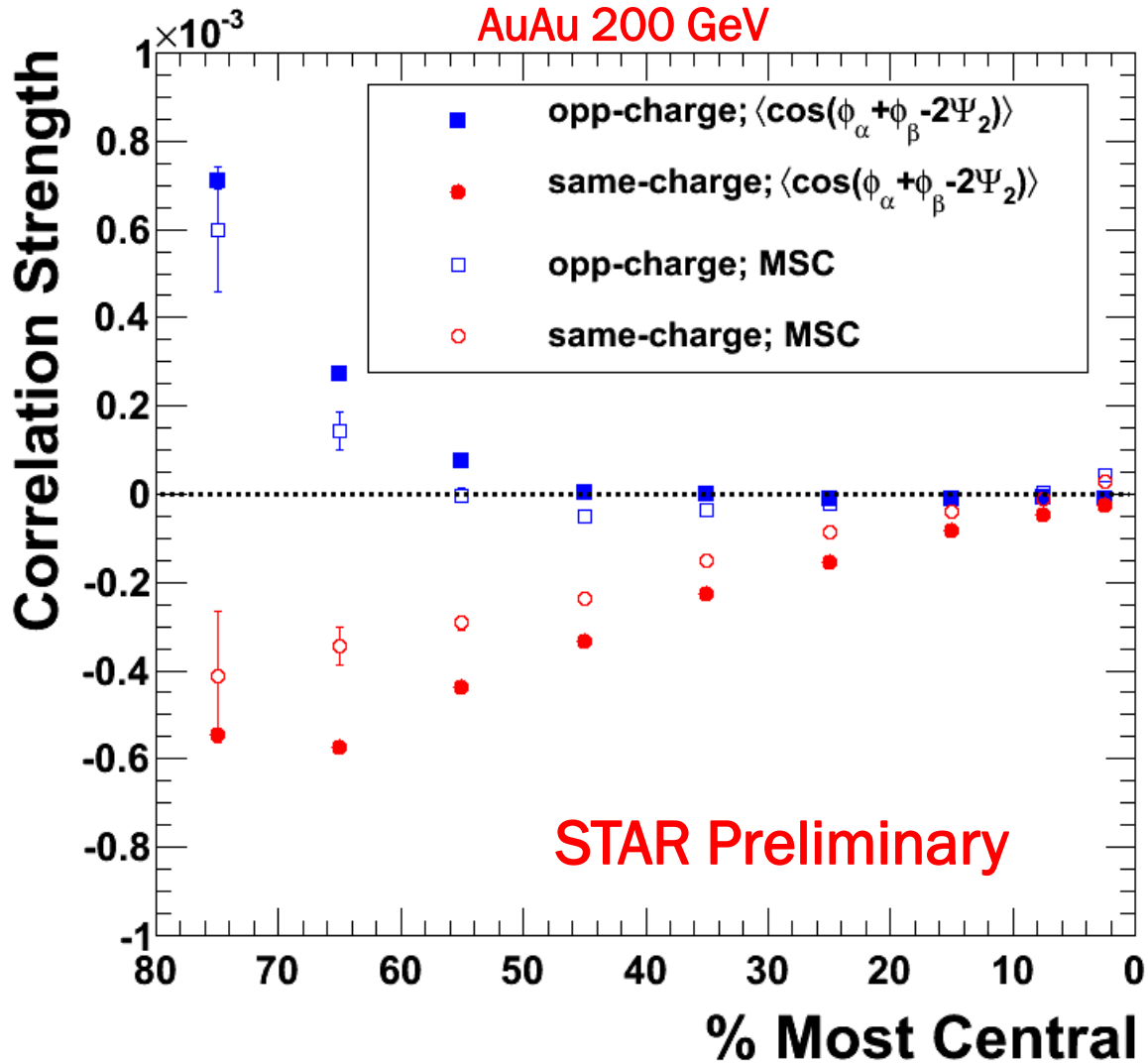
CORRELATOR COMPARISON

Same qualitative trend in both!

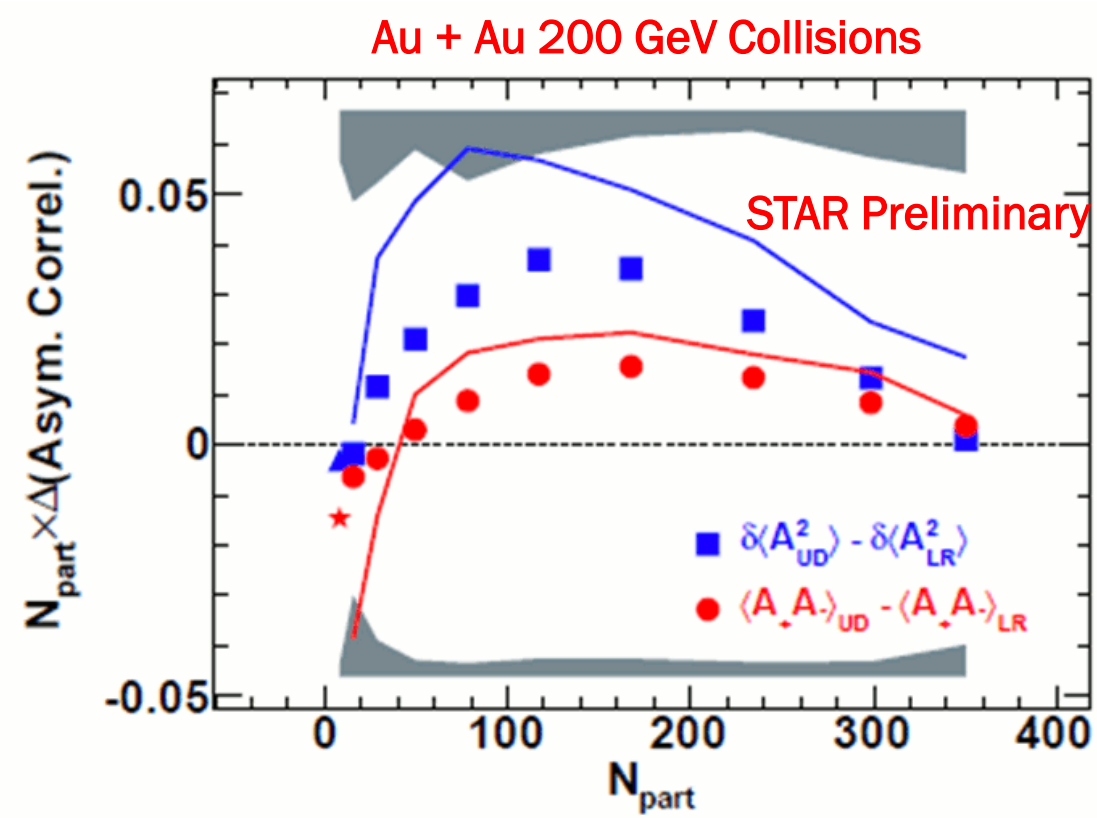
↓

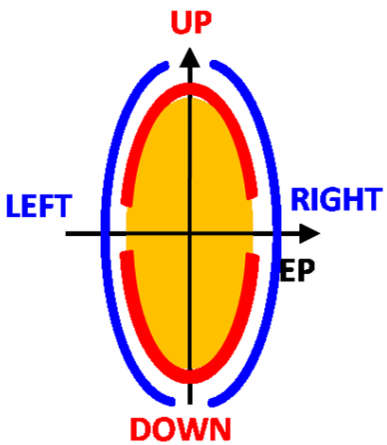
1. A multiplicity asymmetry across the reaction-plane.
2. Opposite charge suppression may not be the case. Likely a P-even background instead.





CHARGE MULTIPLICITY ASYMMETRY CORRELATOR

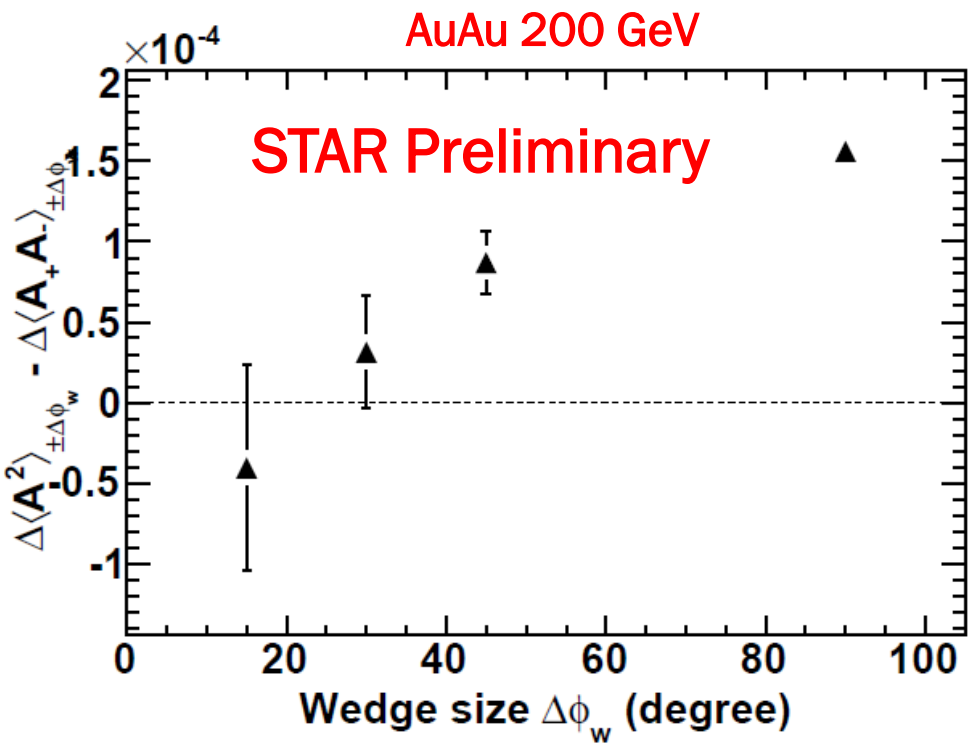




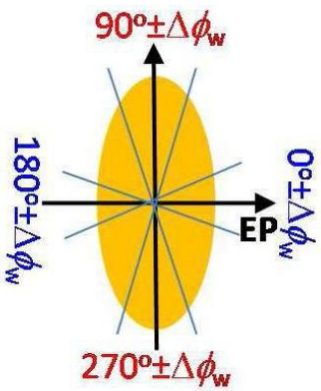
- Same- and opposite-sign both positive in most centralities. Effect cannot be explained by CME alone.

See Quan Wang's poster #583 for details.

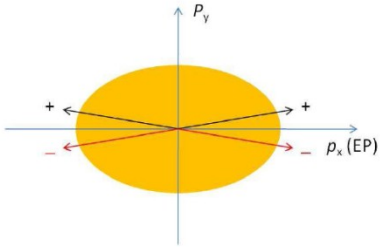
CHARGE MULTIPLICITY ASYMMETRY CORRELATOR



Also done as a function of wedge size.



Suggests that out-plane charge separation fluctuations might be occurring near the event plane.



See Quan Wang's poster #583 for details

SPLIT THE CORRELATOR

Motivation:

Try to separate the simplest effects of charge separation from a possible P-even background.

Define 2 quantities:

$$\Delta Q_{Out} = \left(N_+^T - N_-^T\right) - \left(N_+^B - N_-^B\right)$$

Units of Charge Separation

$$N\left(\Delta Q_{Out}\right)$$

# of events in a ΔQ bin

- **We observe larger charge separation fluctuations across rather than along the event plane.**

RMS N(Δ Q_{out}) > RMS N(ΔQ_{in}).

ΔMSC term

$$MSC = \frac{1}{N_E}\sum_{\Delta Q}\left\langle N\left(\Delta Q\right)\right\rangle\left(MSC_{In}\left(\Delta Q\right) - MSC_{Out}\left(\Delta Q\right)\right)$$

In/Out plane Correlation difference in a given ΔQ bin.

$$+\frac{1}{N_E}\sum_{\Delta Q}\left\langle MSC\left(\Delta Q\right)\right\rangle\left(N_{In}\left(\Delta Q\right) - N_{Out}\left(\Delta Q\right)\right)$$

ΔN term

In/Out plane Event count difference In a given ΔQ bin

SPLIT CORRELATOR

ΔMSC term | ΔN term

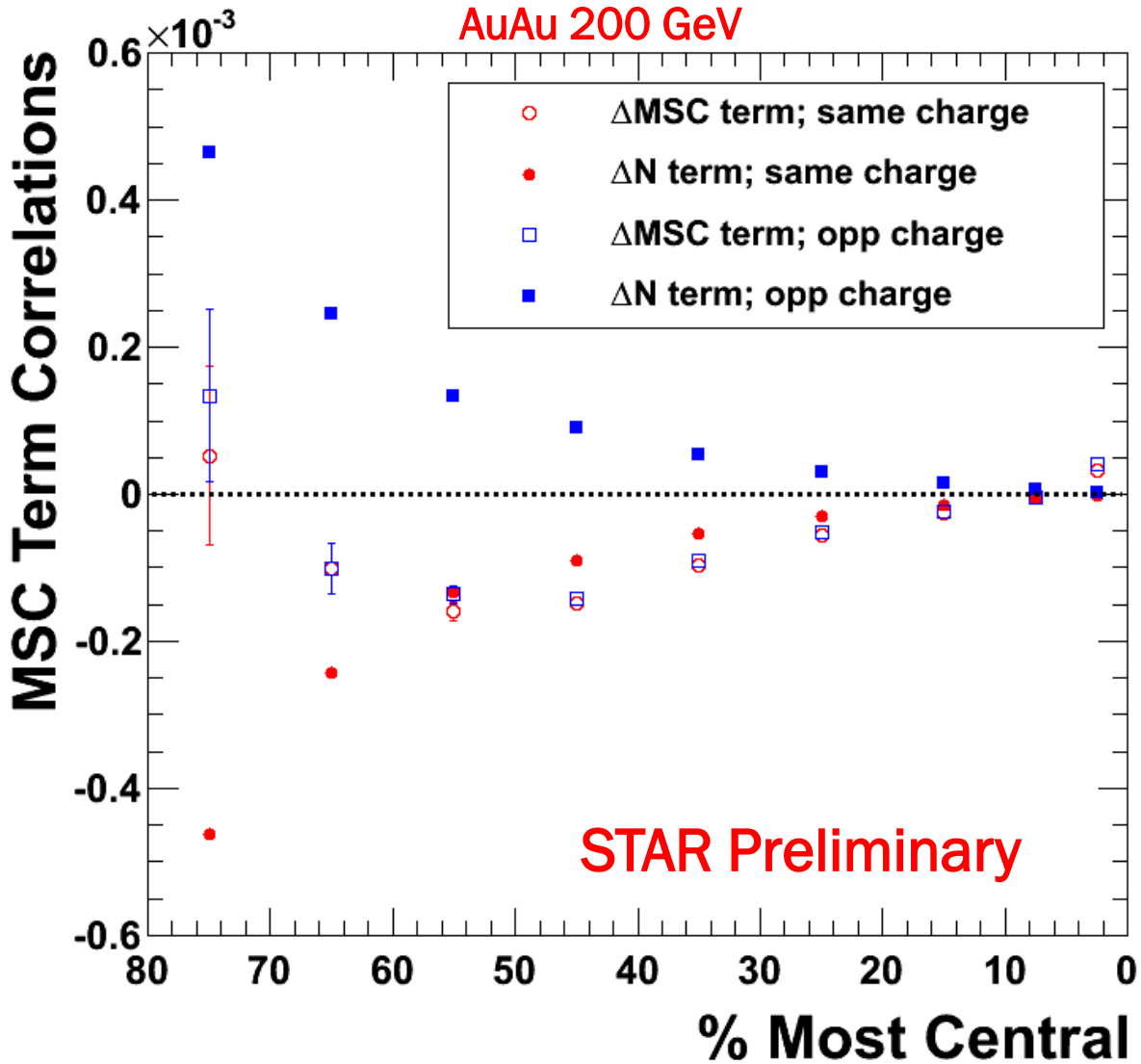
CME

P-even Background

CME 100% in ΔN term?

If yes, CME is likely symmetric. However, a P-even background can also be symmetric.

Answer depends on ΔQ configurations of CME: For ΔQ=+2 we have (2,0),(0,-2),(+1,-1)



CONCLUSIONS

- All correlators are qualitatively consistent with the Chiral Magnetic Effect + P-even background.
- The MSC suggests that a P-even background is likely the cause of the opposite charge suppression.
- The difference between same and opposite charge correlations in $\cos(\varphi_a+\varphi_b-2\psi)$ decreases with decreasing energy.
- A blast wave model with local charge conservation + v_2 can reproduce the difference between opposite charge and same charge correlations in $\cos(\varphi_a+\varphi_b-2\psi)$. This effect in the MSC should be greatly reduced.
- Larger charge separation fluctuations observed **across** rather than along the event plane. It appears to be largely occurring near the event plane.
- Charge separation configurations from the CME needed to determine whether or not the ΔMSC & ΔN terms can isolate the CME.

BACKUP SLIDES

DETAILED EXP OF SPLITTING

$$\Delta Q_{Out} = \left(N_+^T - N_-^T\right) - \left(N_+^B - N_-^B\right)$$

$$N(\Delta Q)$$

$$MSC = \frac{1}{N_E}\sum_{\Delta Q}\langle N(\Delta Q)\rangle\underline{(MSC_{In}(\Delta Q) - MSC_{Out}(\Delta Q))} + \frac{1}{N_E}\sum_{\Delta Q}\langle MSC(\Delta Q)\rangle\underline{(N_{In}(\Delta Q) - N_{Out}(\Delta Q))}$$

The avg probability of this state

ΔQ configuration difference

For ΔQ=+2 we have (2,0),(0,-2),(+1,-1)

Probability difference

The avg correlation of this state

These ideas are supported by some simulations we've done

A SIMULATION

Pure Statistical model + a1

Inputs:

- Uniformly distributed reaction plane angle ψ
- Charged particles: 100 positive and 100 negative
- *v2 = 5%, same for positive and negative particles*
- *a1 = ±2%, opposite signs for positive and negative particles*
- *a1 randomly flips sign event-by-event*
- 2nd-order EP reconstructed from the input particles

Outputs:

- 2nd-order EP resolution ~ 56%
- measured *v2 = 5%, the same as input*
- measured full correlation <cos(φ1+φ2-2ψ)> = ±4*10-4 for opposite and same sign, respectively.
- **MSC ~ ±2.55*10-4** for opposite and same, respectively.
- **MSC(ΔQ=0) =0** for both same and opposite sign.
- **When ΔQ = N (!=0), MSC is still zero** for both same and opposite sign!

Thus, the signal is entirely isolated in the ΔN term for this case

ANOTHER SIMULATION

Embedded resonance: $\rho \longrightarrow \pi^{+}+\pi^{-}$

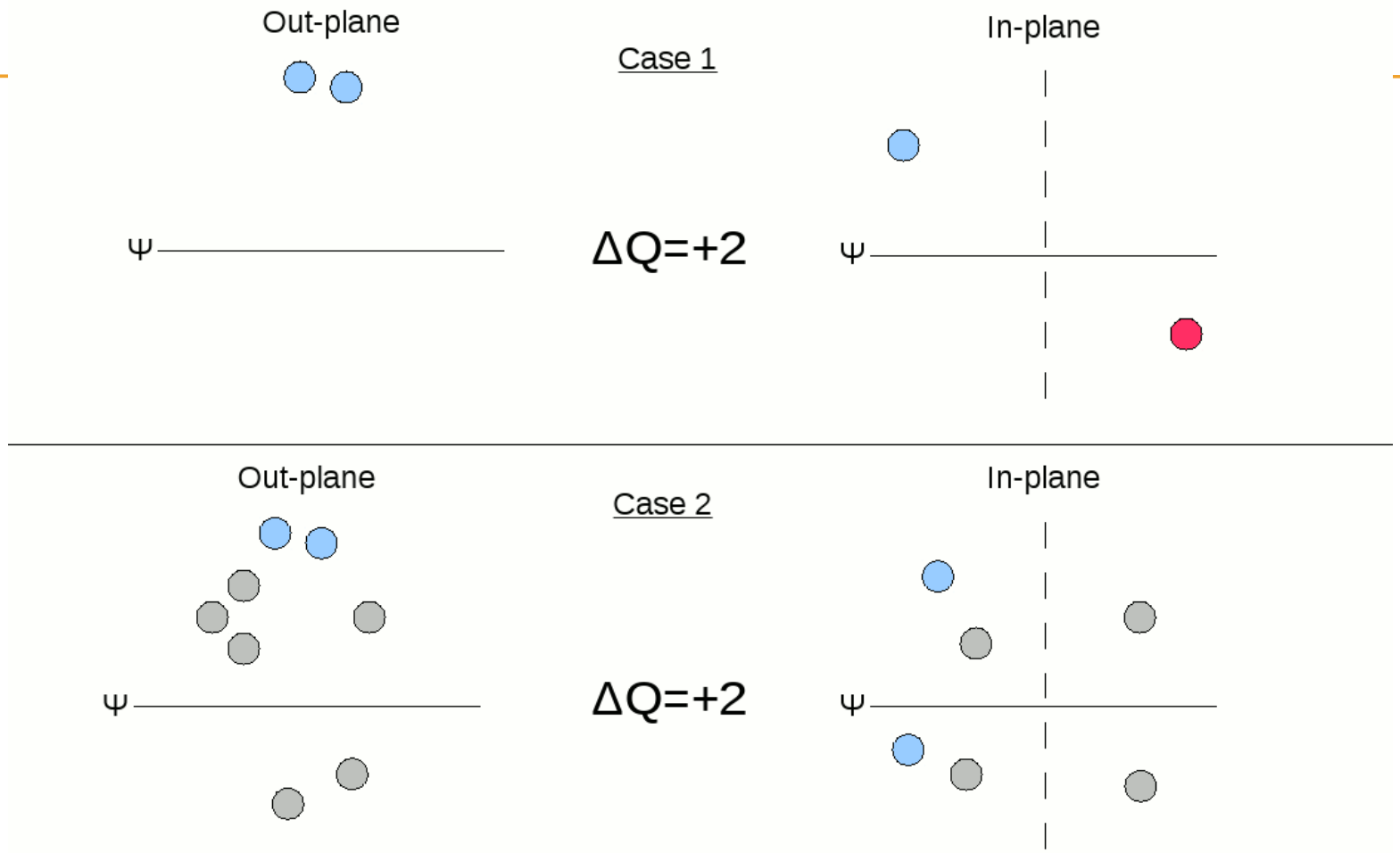
Inputs:

- true reaction plane
- 100 positive and 100 negative particles: *v2 = 5% and a1 = 2%.*
- 10 ρ each event, with *v2 = 5% and a1 = 0.*
- ρ has a uniform *η distribution [-1, 1], and fixed pT at 0.5 GeV/c.*
- daughter pion has a momentum of 0.358 GeV/c in the resonance center-of-mass frame, which is boosted to lab frame later.

Outputs:

- **MSC ~ 3.67*10-4 and -3.41*10-4 for oppo and same sign**.
- MSC for the oppo sign has a magnitude 2.6*10-5 higher than the same sign, since the resonance increases the oppo sign correlation. 3.1*10-3 /121
- **MSC(ΔQ=0) ~ 0** for both same- and oppo-sign correlations.

ΔMSC Term

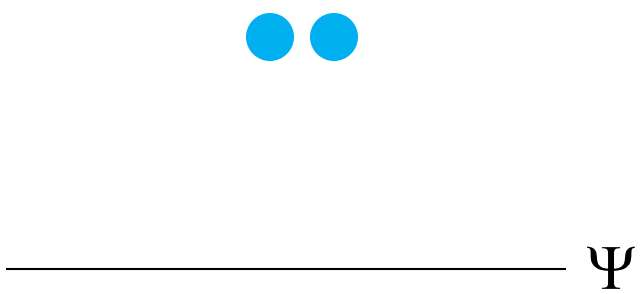


$$\Delta MSC\_term = \frac{1}{N_E} \sum_{\Delta Q} \langle N(\Delta Q) \rangle (MSC_{In}(\Delta Q) - MSC_{Out}(\Delta Q))$$

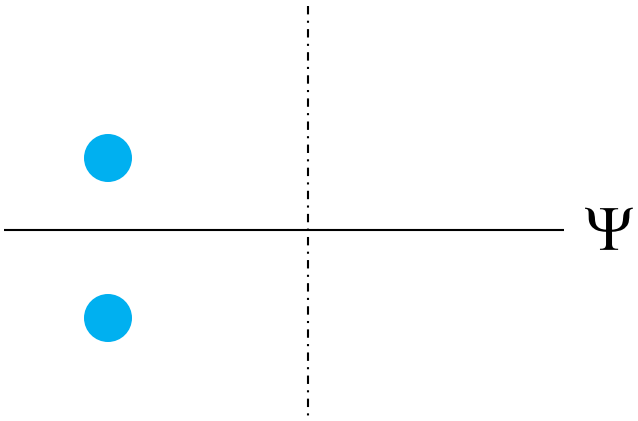
This term is sensitive to the difference between MSC_{in} and MSC_{out} in each ΔQ state.

ΔN TERM

$$\Delta Q_{Out} = +2$$



$$\Delta Q_{In} = +2$$



$$\Delta N\_term = \frac{1}{N_E} \sum_{\Delta Q} \langle MSC(\Delta Q) \rangle (N_{In}(\Delta Q) - N_{Out}(\Delta Q))$$

This term is sensitive to the difference between N_{in} and N_{out} in each ΔQ state.

MSC DERIVATION

$$\left\langle \cos\left(\phi_a - \Psi_{EP}\right)\cos\left(\phi_b - \Psi_{EP}\right)\right\rangle - \left\langle \sin\left(\phi_a - \Psi_{EP}\right)\sin\left(\phi_b - \Psi_{EP}\right)\right\rangle$$

$$= \left\langle M_a S_a M_b S_b \right\rangle_{In-plane} - \left\langle M_a S_a M_b S_b \right\rangle_{Out-plane}$$

$$\left\langle MS \right\rangle = \left\langle M \right\rangle \left\langle S \right\rangle$$

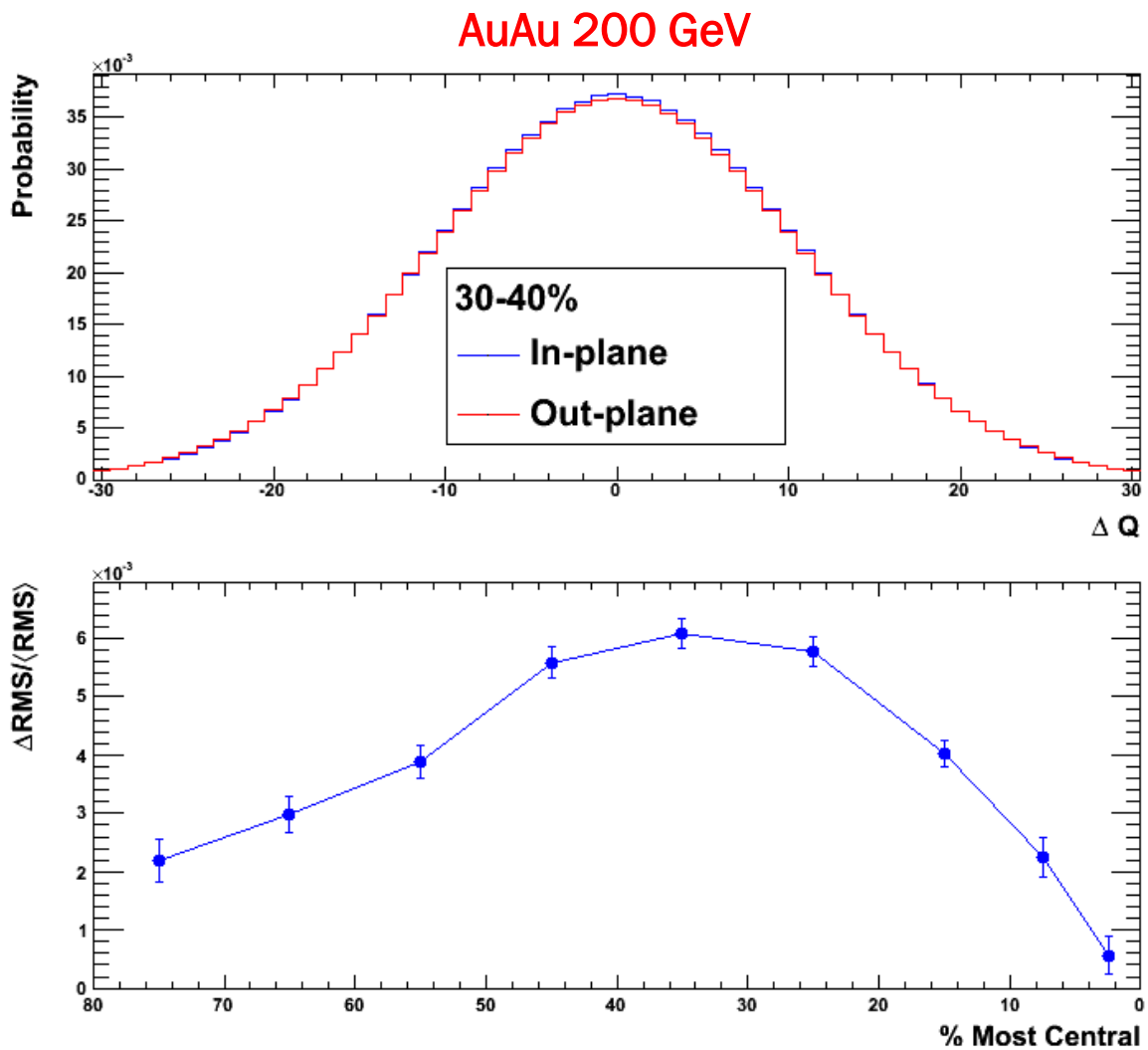
$$\left\langle M_a M_b \right\rangle = \left\langle M \right\rangle^2$$

$$\left\langle M \right\rangle \rightarrow \frac{2}{\pi}$$

$$\rightarrow \left(\frac{2}{\pi}\right)^2 \left(\left\langle S_a S_b \right\rangle_{In-plane} - \left\langle S_a S_b \right\rangle_{Out-plane}\right)$$

ΔQ DISTRIBUTION

- Out-plane distribution is always wider than In-plane.
- Calculated from 2 equal Multiplicity sub-events.
- Not corrected for reaction plane resolution.
- Flowing resonances may also contribute here.

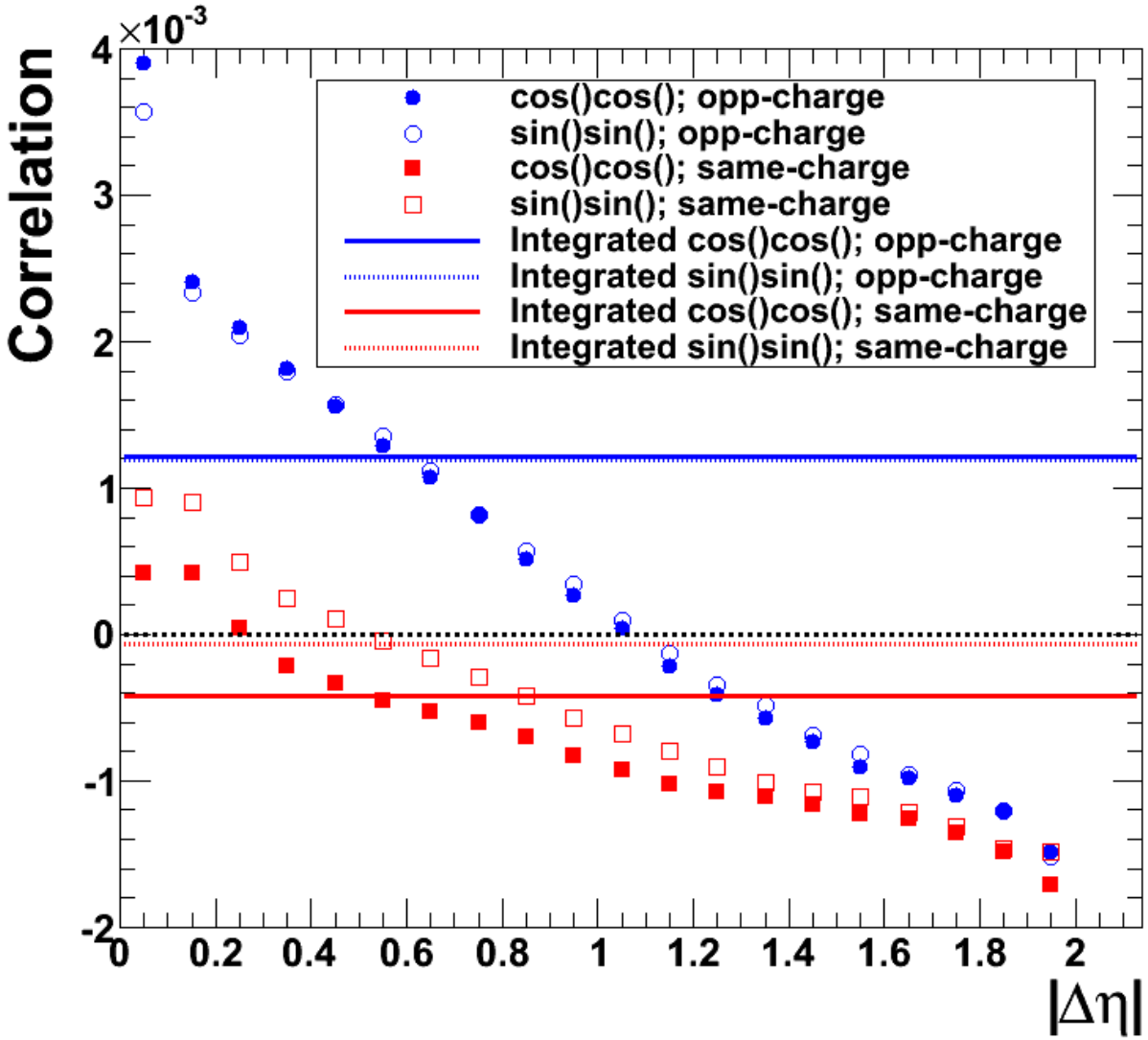


ΔETA DEPENDENCE

40-60% Centrality

Solid Points: cos()cos()

Hollow Points: sin()sin()

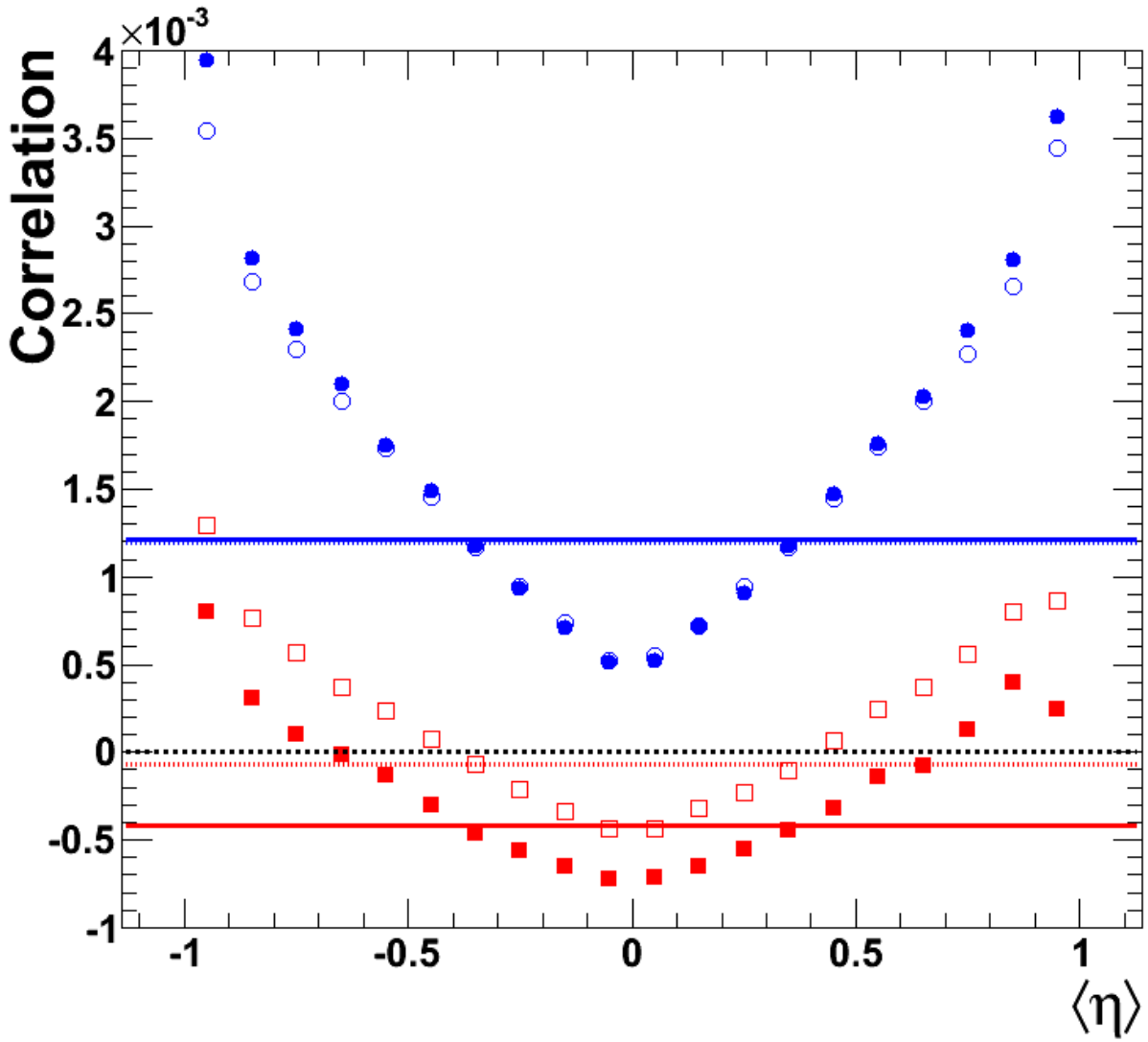


AVERAGE ETA

40-60% Centrality

Solid Points: cos()cos()

Hollow Points: sin()sin()

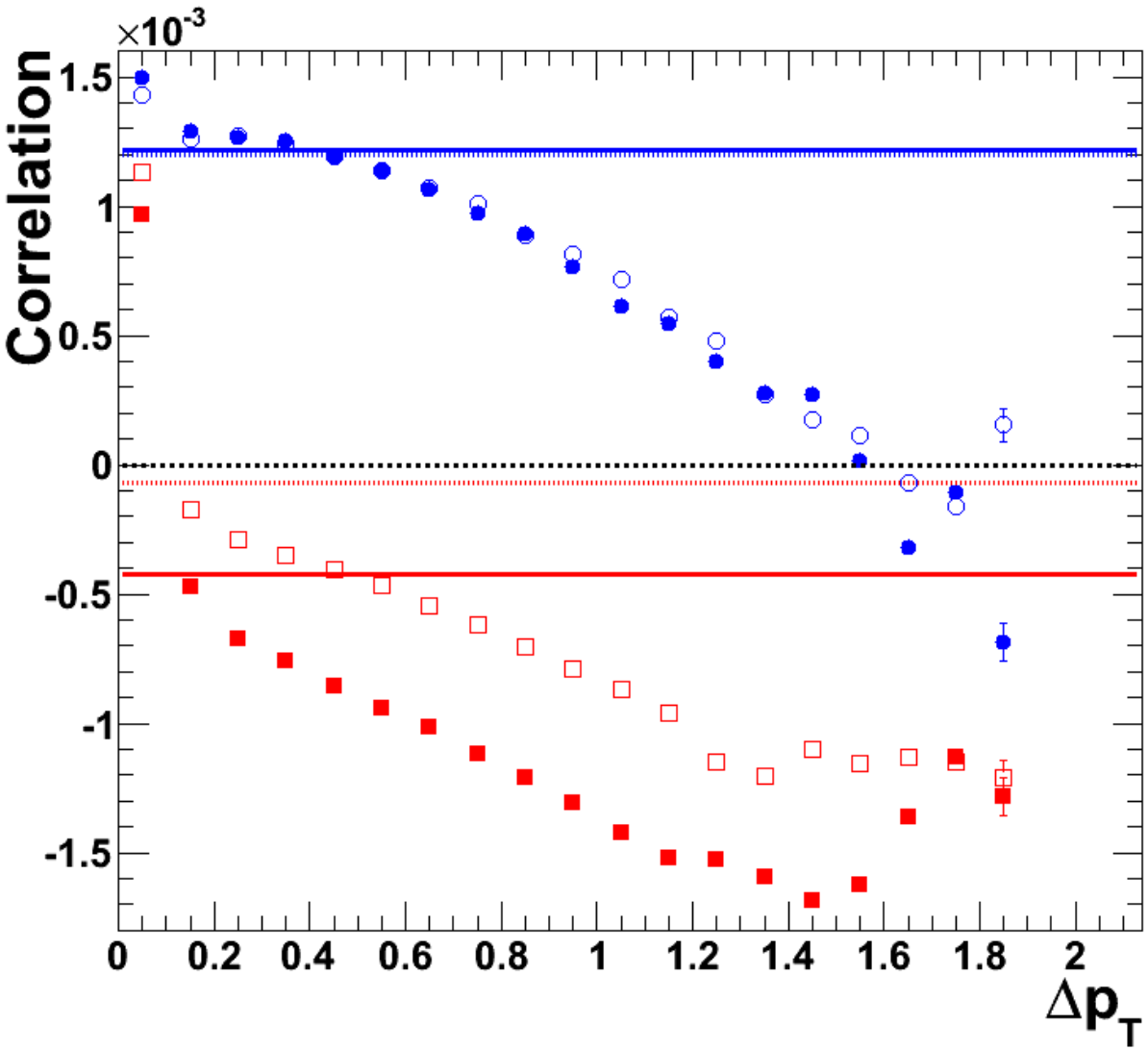


ΔPT

40-60% Centrality

Solid Points: cos()cos()

Hollow Points: sin()sin()



AVERAGE PT

40-60% Centrality

Solid Points: cos()cos()

Hollow Points: sin()sin()