Musings on Present and Future Azimuthal Charge-asymmetry Measurements

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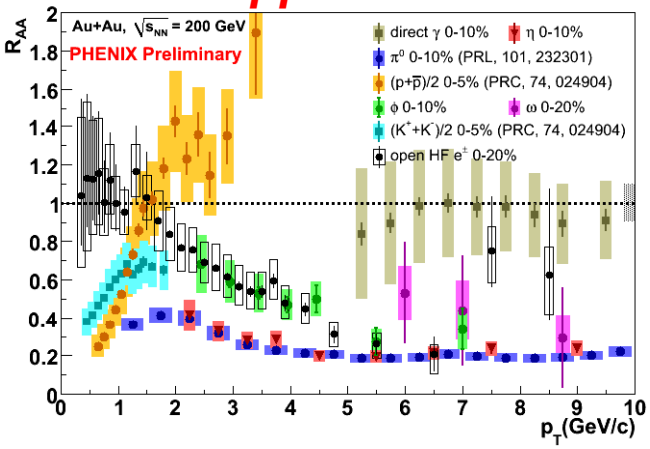
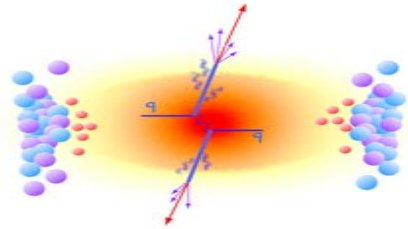
Charge

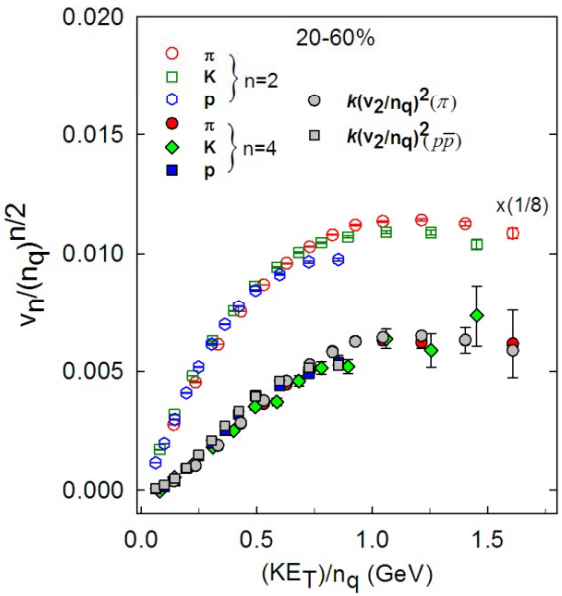
1. *Reiterate why charge-asymmetry measurements are important*
2. *Review the methodologies exploited in PHENIX and give a summary of current results from:*
   - *the two particle correlation technique*
   - *the multi-particle correlation technique (New)*
3. *Give a quick survey of measurements which could be insightful*

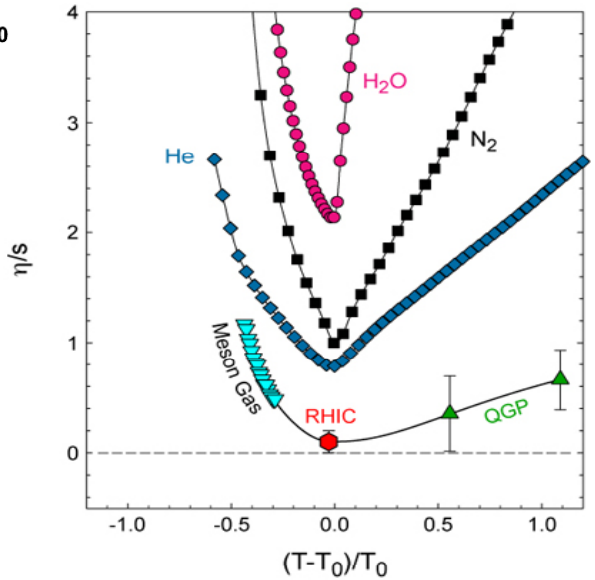
Jet suppression

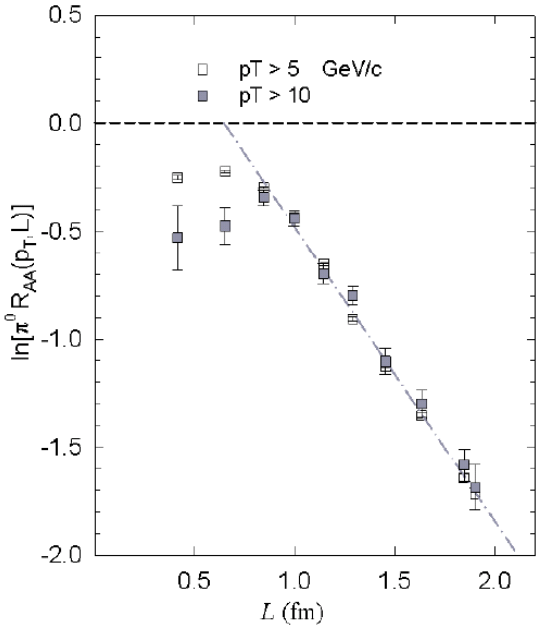




Flow scales with q_n

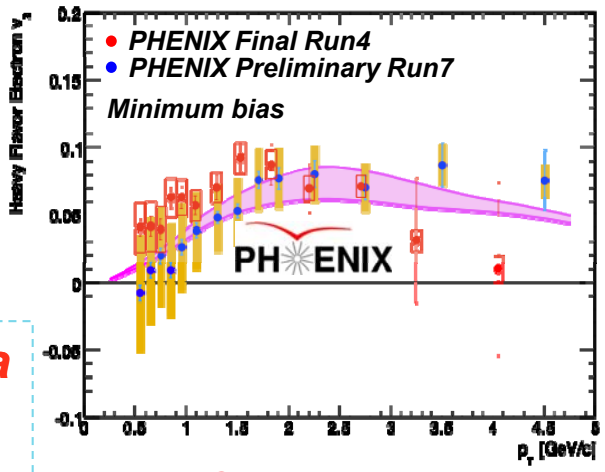






Jet suppression scales

A strongly coupled plasma is produced in heavy ion Collisions at RHIC

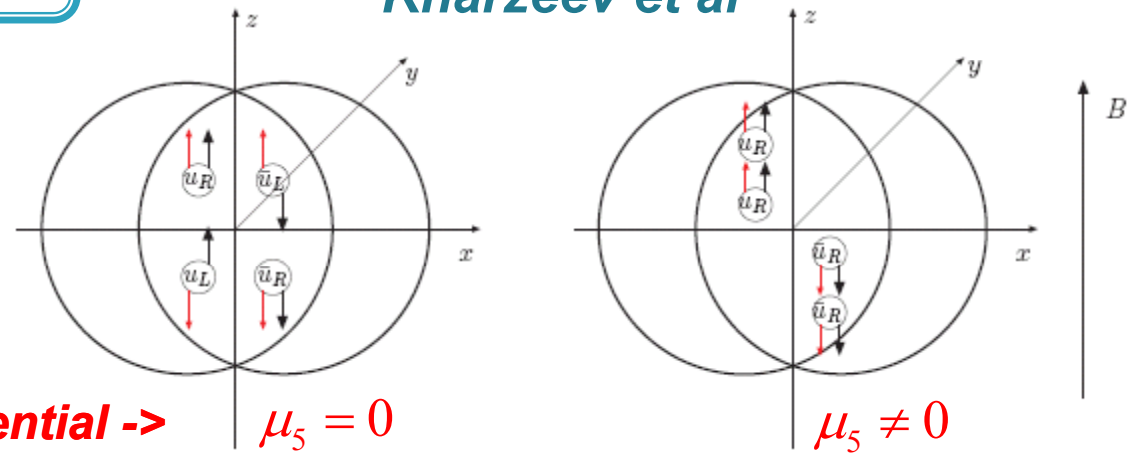


Charm Flows

The Central Question

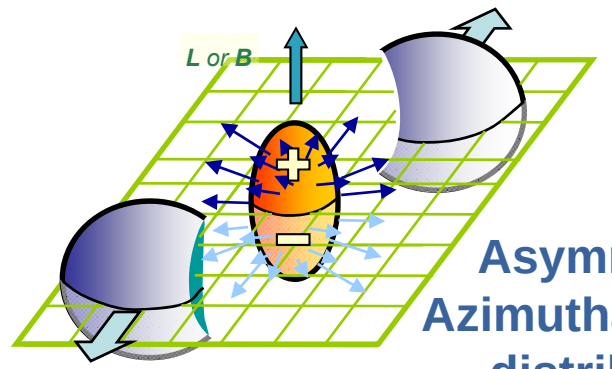
Chiral magnetic effect
Kharzeev et al

Axial anomaly ->
parity odd metastable domains
in which $u_L(\bar{u}_L) \neq u_R(\bar{u}_R)$



Chiral chemical potential ->

Does the new phase of QCD matter created in RHIC collisions provide new insights on P/CP invariance of the strong interaction ? If it does, how do we tell ?

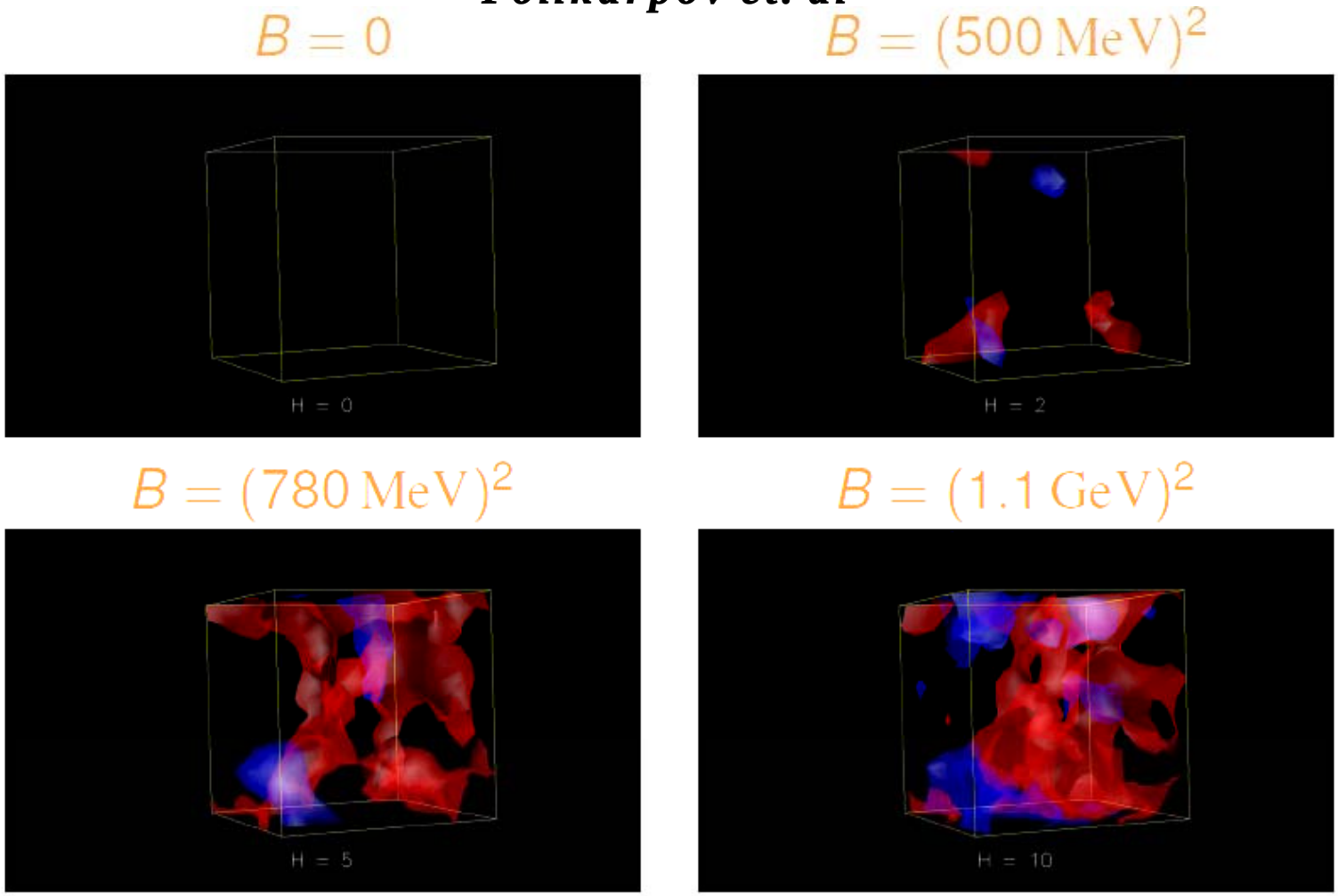


Asymmetric Azimuthal charge distribution

Axial anomaly ->
anomalous global symmetry current in hydrodynamics
D. Son et al

Chiral Magnetic Effect on the Lattice

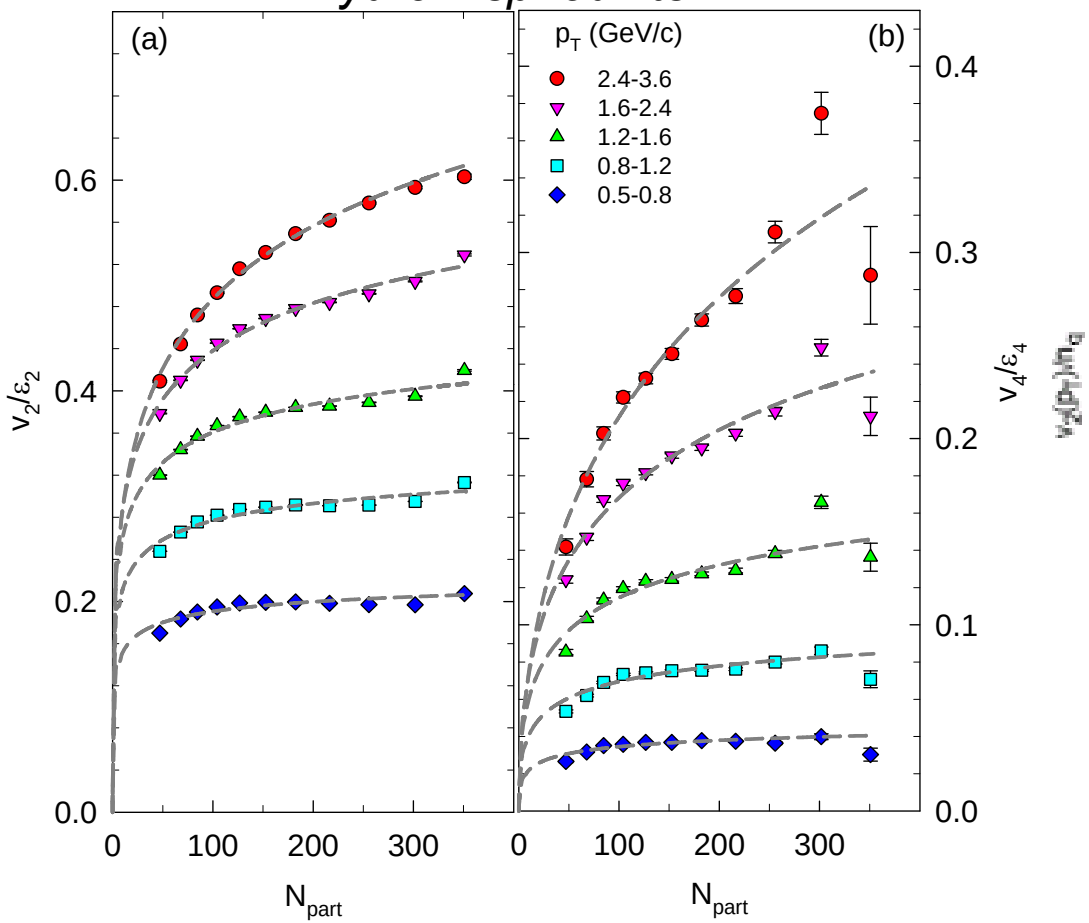
Polikarpov et. al



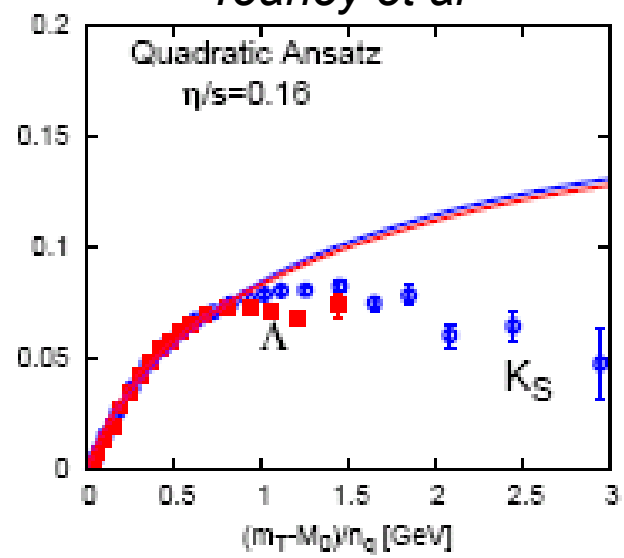
Lattice calculations now confirm the chiral magnetic effect

The Hydrodynamic ansatz "works" for flow

Hydro inspired fits



Teaney et al



Viscous hydrodynamics accounts for harmonic flow at RHIC

Anomalous global symmetry current in hydrodynamics ?

Azimuthal charge-asymmetry studies could provide:

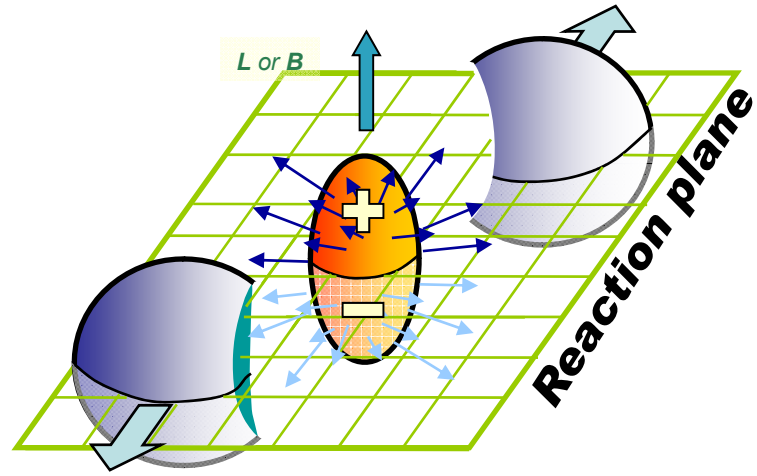
✓ ***A clear demonstration of the non-trivial topological structure of the QCD vacuum***

A prerequisite for local P-violation in strongly interacting matter is deconfinement [with restored chiral symmetry]

✓ **Asymmetry studies could also be an indispensible tool for insights on deconfinement [and chiral symmetry restoration]**

Current analysis status!

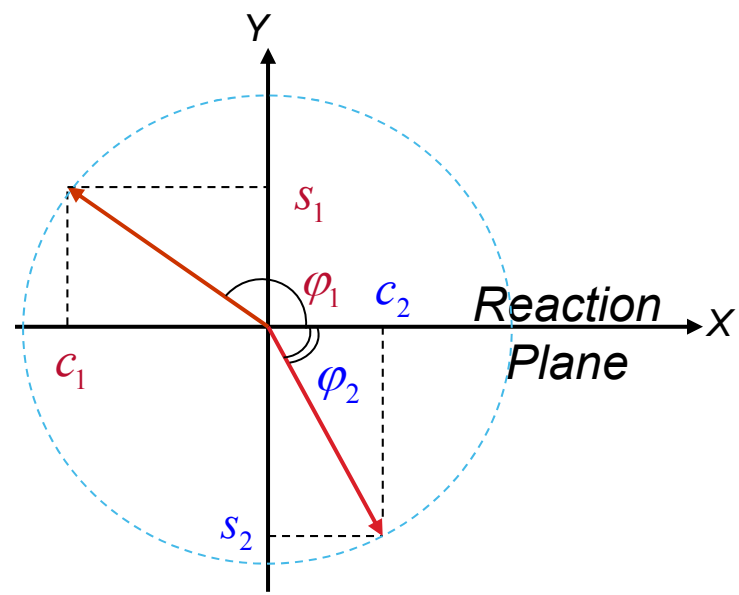
Two-particle correlation Probe



$$\frac{dN_\pm}{d\phi} \propto 1 + 2v_1\cos(\Delta\phi) + 2v_2\cos(2\Delta\phi) + \ldots$$
$$+ \; 2a_{1,\pm}\sin(\Delta\phi) + \ldots, \quad \Delta\phi = \phi - \Psi_{RP}$$

$$\langle\cos(\phi_\alpha + \phi_\beta - 2\Psi_{RP})\rangle =$$
$$= \langle\cos\Delta\phi_\alpha \cos\Delta\phi_\beta\rangle - \langle\sin\Delta\phi_\alpha \sin\Delta\phi_\beta\rangle$$
$$= [\langle v_{1,\alpha}v_{1,\beta}\rangle + B^{in}] - [\langle a_\alpha a_\beta\rangle + B^{out}].$$

$\alpha, \beta = -, +$ $\quad v_1 = 0\,,\; B^{in} \approx B^{out}$

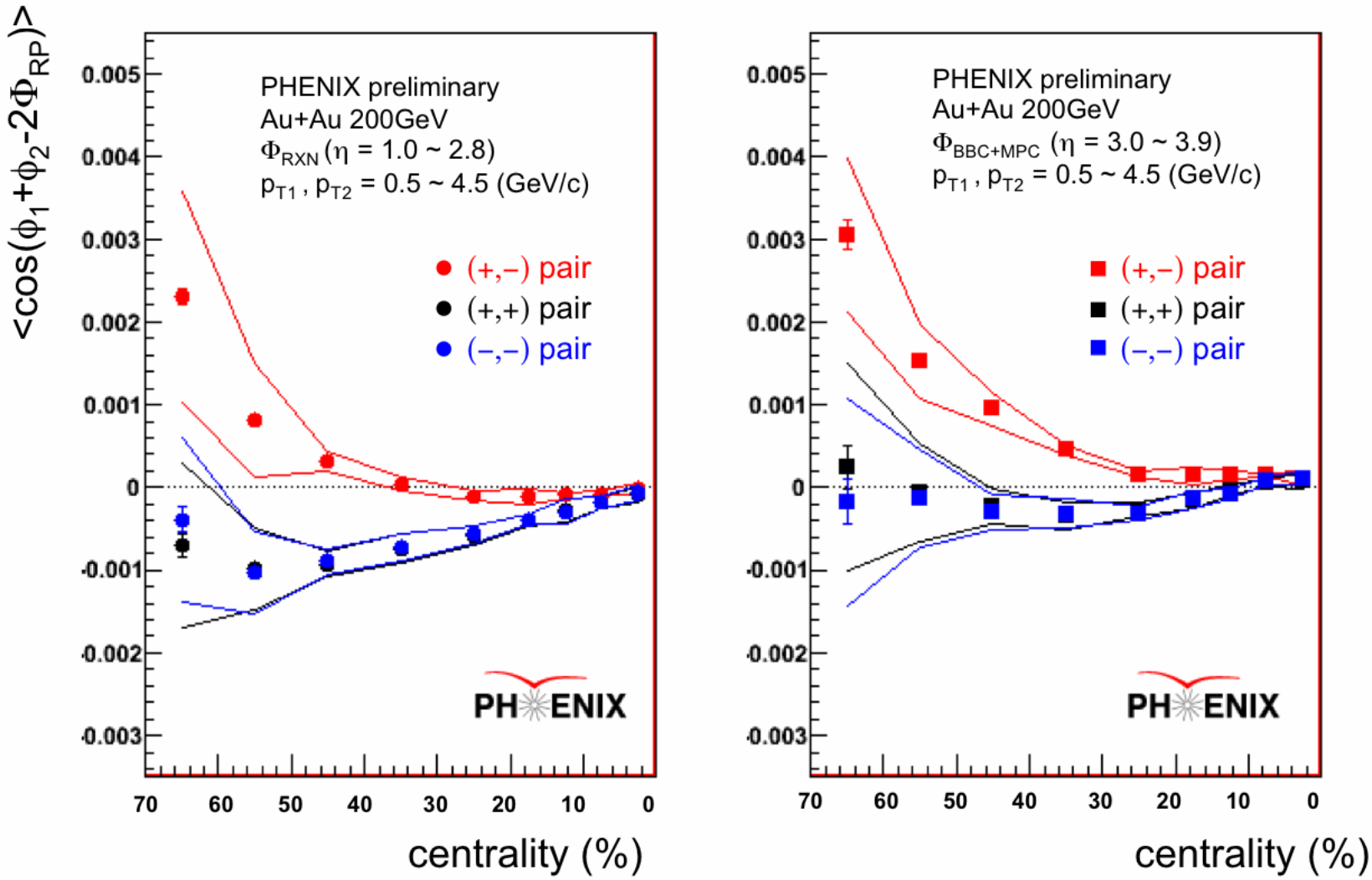


Averaging is performed over all pairs in a given event and then over all events with a given centrality

✓*acceptance correction accounted for with event mixing*

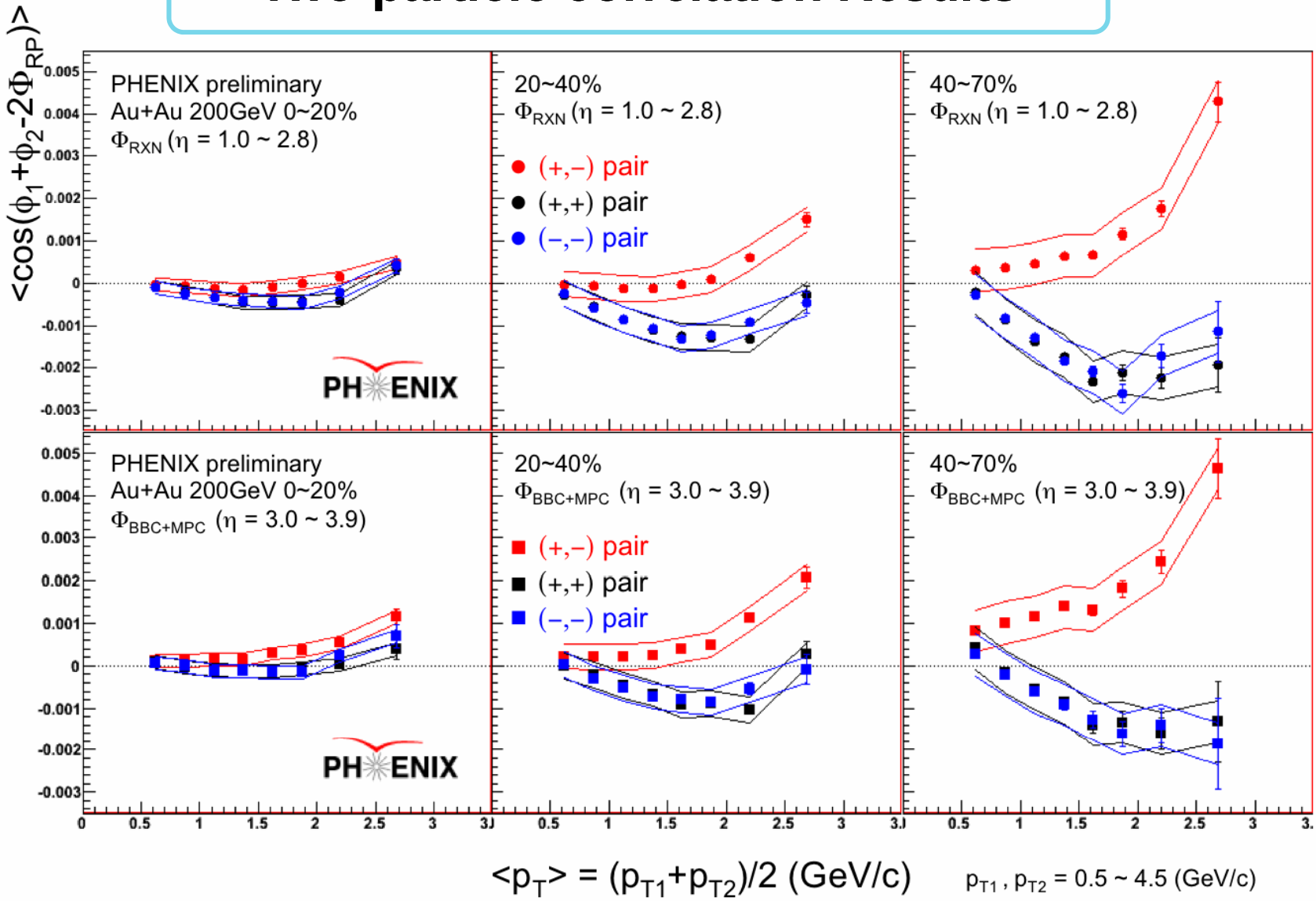
✓*reaction plane resolution correction*

Two-particle correlation Results



Signal is sensitive to collision centrality

Two-particle correlation Results



Signal grows with centrality and p_T

Two-particle correlation Caveat

$$\langle \cos(\phi_\alpha + \phi_\beta - 2\Psi_{RP}) \rangle =$$
$$= \langle \cos \Delta\phi_\alpha \cos \Delta\phi_\beta \rangle - \langle \sin \Delta\phi_\alpha \sin \Delta\phi_\beta \rangle$$
$$= [\langle v_{1,\alpha} v_{1,\beta} \rangle + B^{in}] - [\langle a_\alpha a_\beta \rangle + B^{out}].$$

$\alpha, \beta = -, +$

$v_1 = 0$, $B^{in} \approx B^{out}$

$B^{in} \approx B^{out}$?

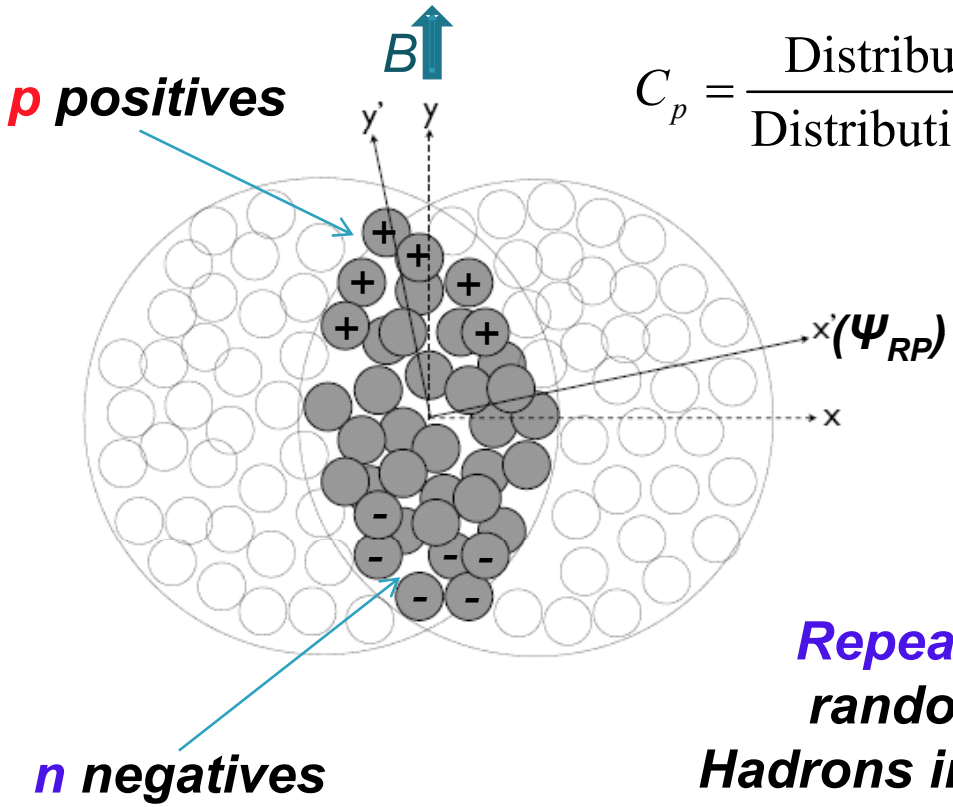
Flow dominated background

Resolution

Invent charge sensitive correlators which are insensitive to flow

Perform control experiments

The multi-particle charge-sensitive correlation function (C_p)



$$C_p = \frac{\text{Distribution with Charge Correlations}}{\text{Distribution without Charge Correlations}}$$

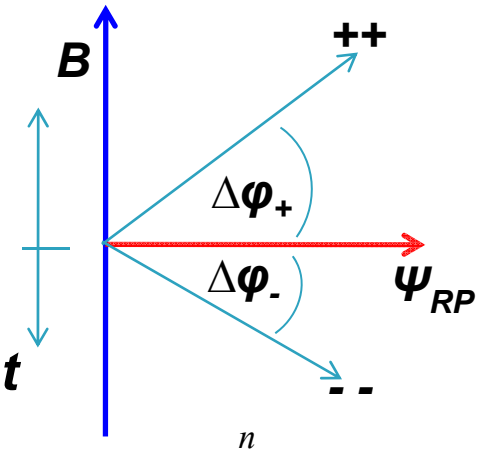
Task

Generate two distributions

$$\left\langle S_p^{h+} \right\rangle = \frac{\sum_1^p \sin(\Delta\varphi_+)}{p}$$

$$\Delta S = \left\langle S_p^{h+} \right\rangle - \left\langle S_n^{h-} \right\rangle$$

Build $N_f(\Delta S)$



Repeat for n and p randomly chosen Hadrons in the same event

$$\Delta S = \left\langle S_p^{h\pm} \right\rangle - \left\langle S_n^{h\pm} \right\rangle$$

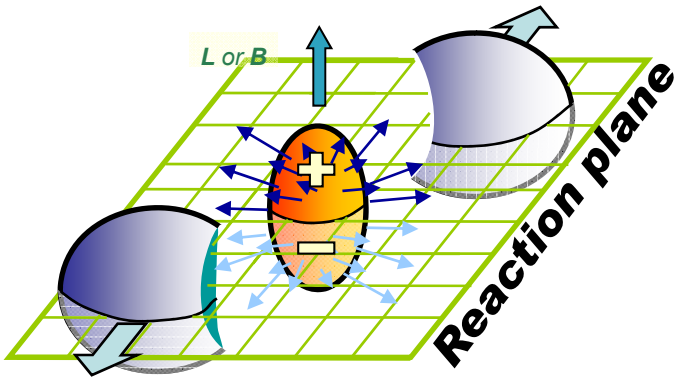
Build $N_R(\Delta S)$

$$\left\langle S_n^{h-} \right\rangle = \frac{\sum_1^n \sin(\Delta\varphi_-)}{n}$$

$$C_p(\Delta S) = \frac{N_F(\Delta S)}{N_R(\Delta S)}$$

C_p is an in-event correlator

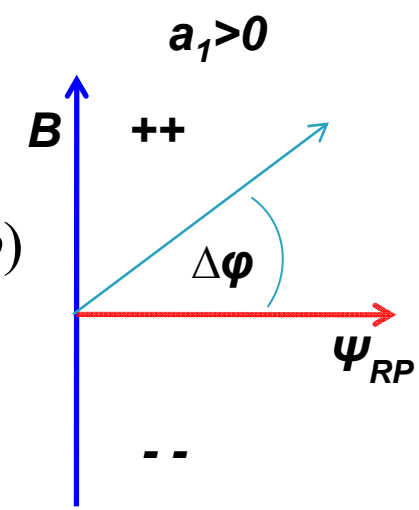
Properties of C_p



Charge sensitive correlation function

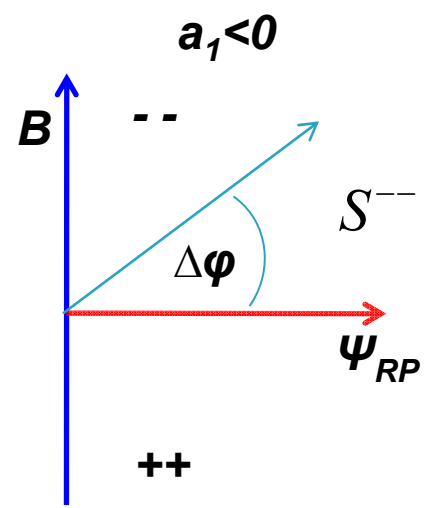
$$\frac{d^2N}{dp_T d\varphi} \propto \left[1 + 2v_2\cos\left(2\left(\varphi - \Psi_{RP}\right)\right) + 2v_4\cos\left(4\left(\varphi - \Psi_{RP}\right)\right) + 2a_1^{\pm}\sin\left(\left(\varphi - \Psi_{RP}\right)\right)\right]$$

$S^{h+} = \sin(\Delta\varphi)$



Positive charge favor B

$S^{--} = \sin(\Delta\varphi)$



Negative charge favor B

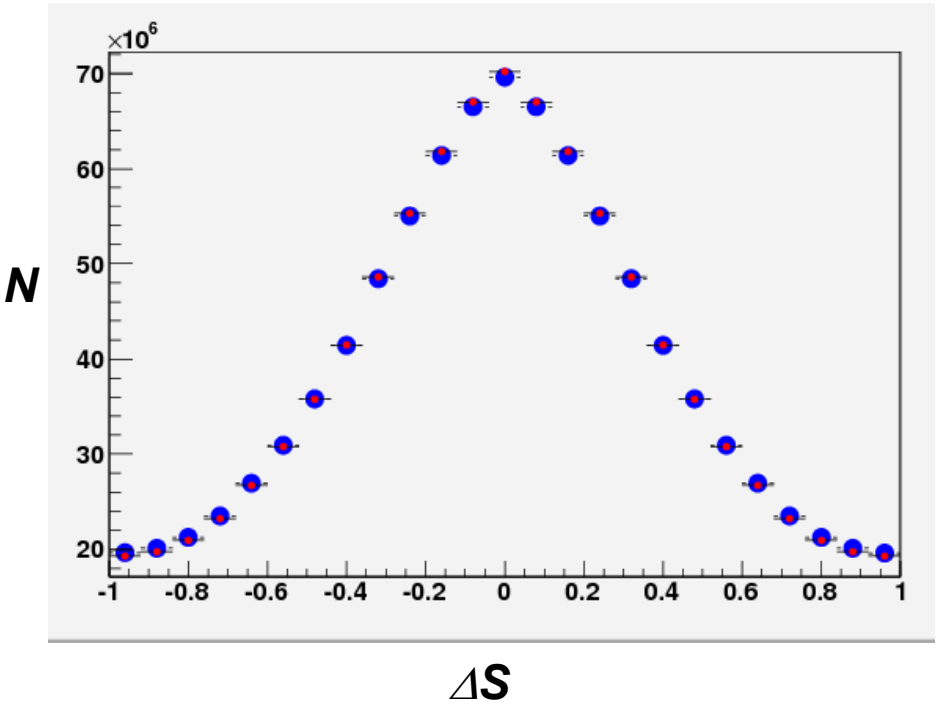
Properties of C_p

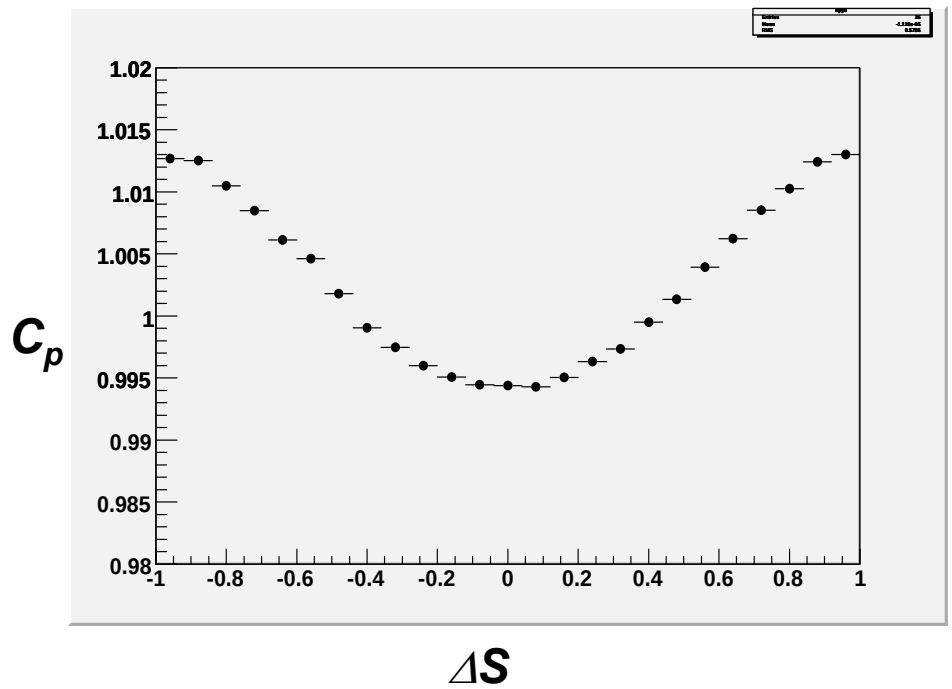
Simulated Results

a_1 < changes sign from event to event

$$N\left(\left\langle S_p^{h+}\right\rangle - \left\langle S_n^{h-}\right\rangle\right)$$ ***(Blue points)***

$$N\left(\left\langle S_p^{h\mp}\right\rangle - \left\langle S_n^{h\mp}\right\rangle\right)$$ ***(Red points)***



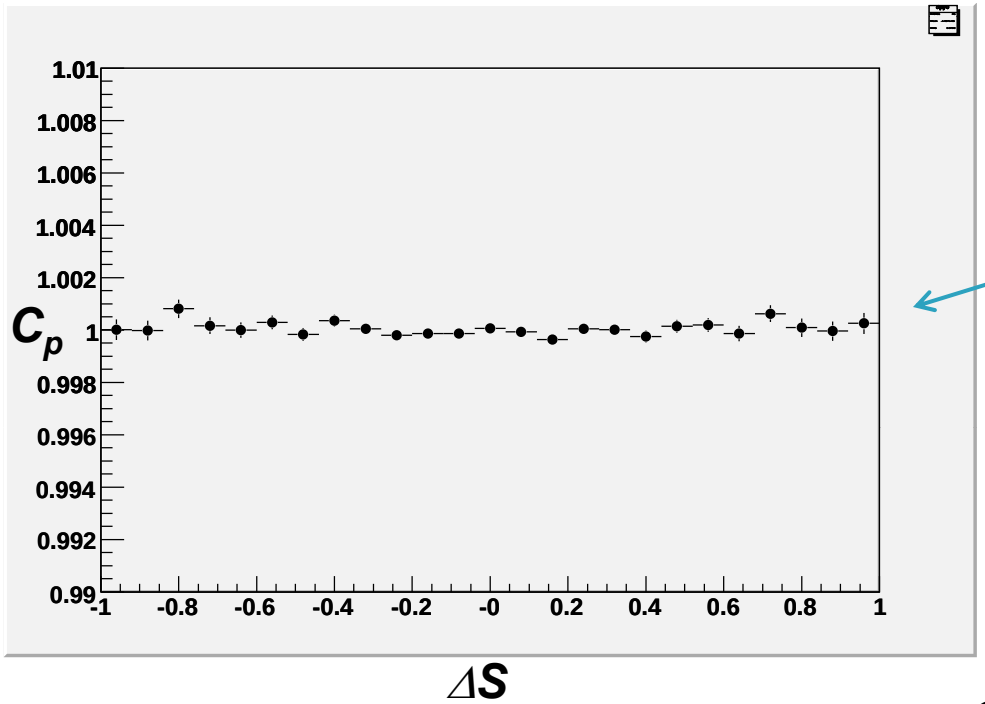


Numerator slightly broader
C_p concave and symmetric

Properties of C_p

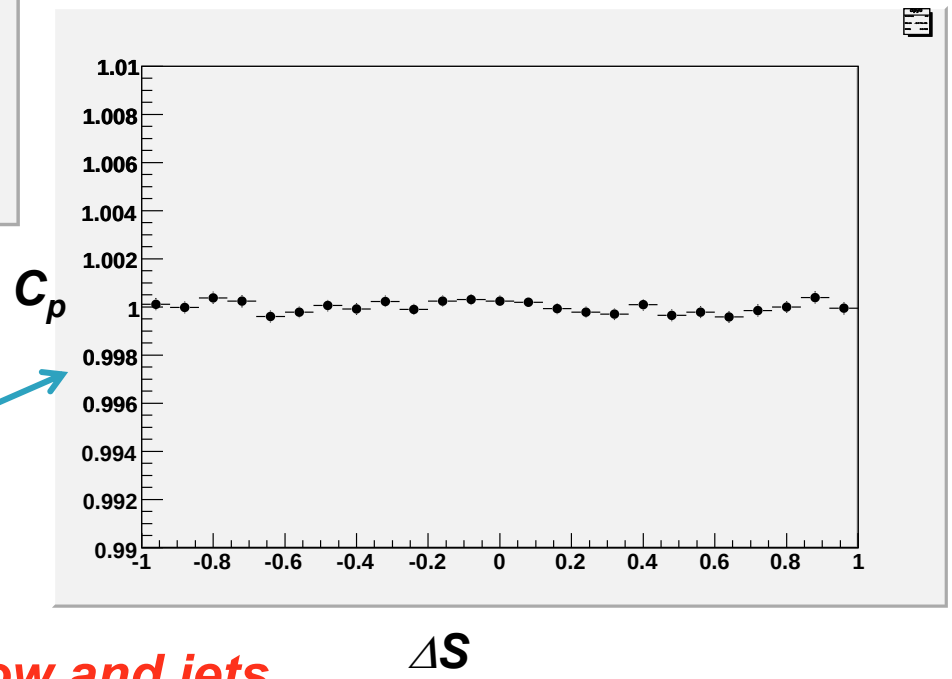
Simulated Results

C_p is an in-event correlator
→ Several benefits



Flow : Yes
Parity violating signal : No
Decay : No

Flat response to flow



Jet : Yes
Parity violating signal : No
Decay : No

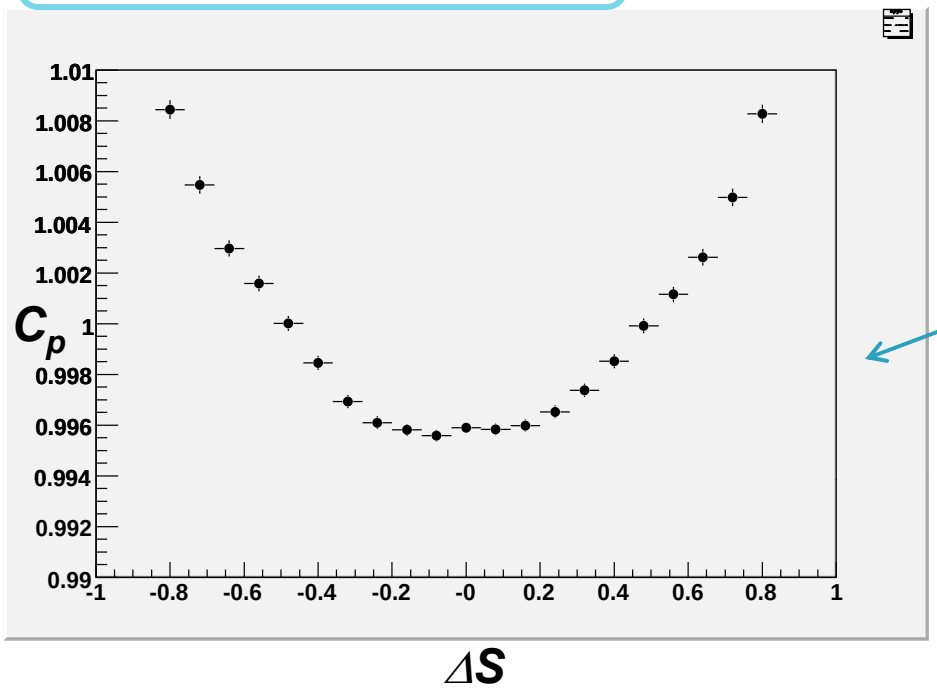
Flat response to jets

C_p insensitive to flow and jets

Properties of C_p

Simulated Results

C_p is an in-event correlator
→ Several benefits

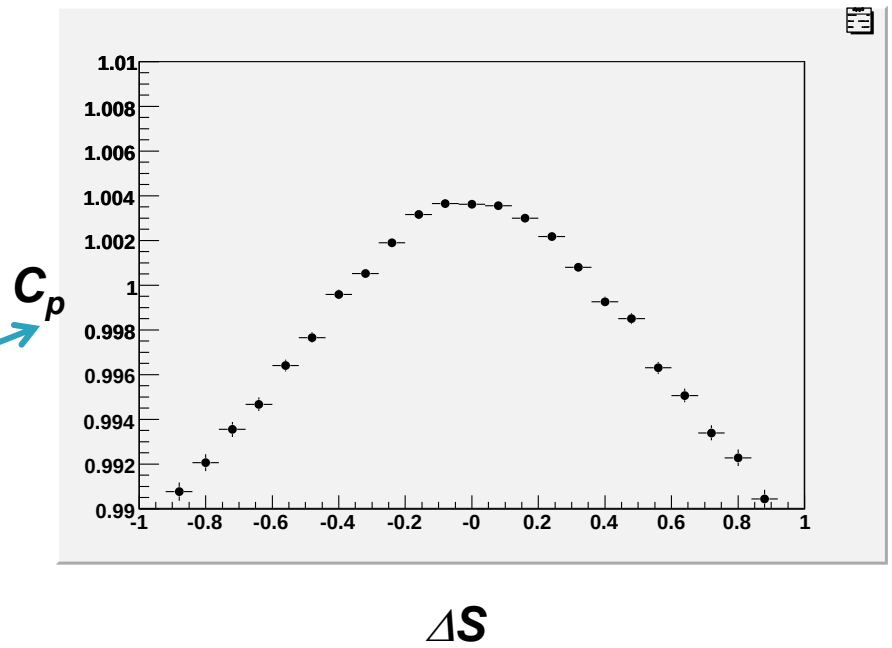


Flow : Yes
Parity violating signal : Yes
Decay : No

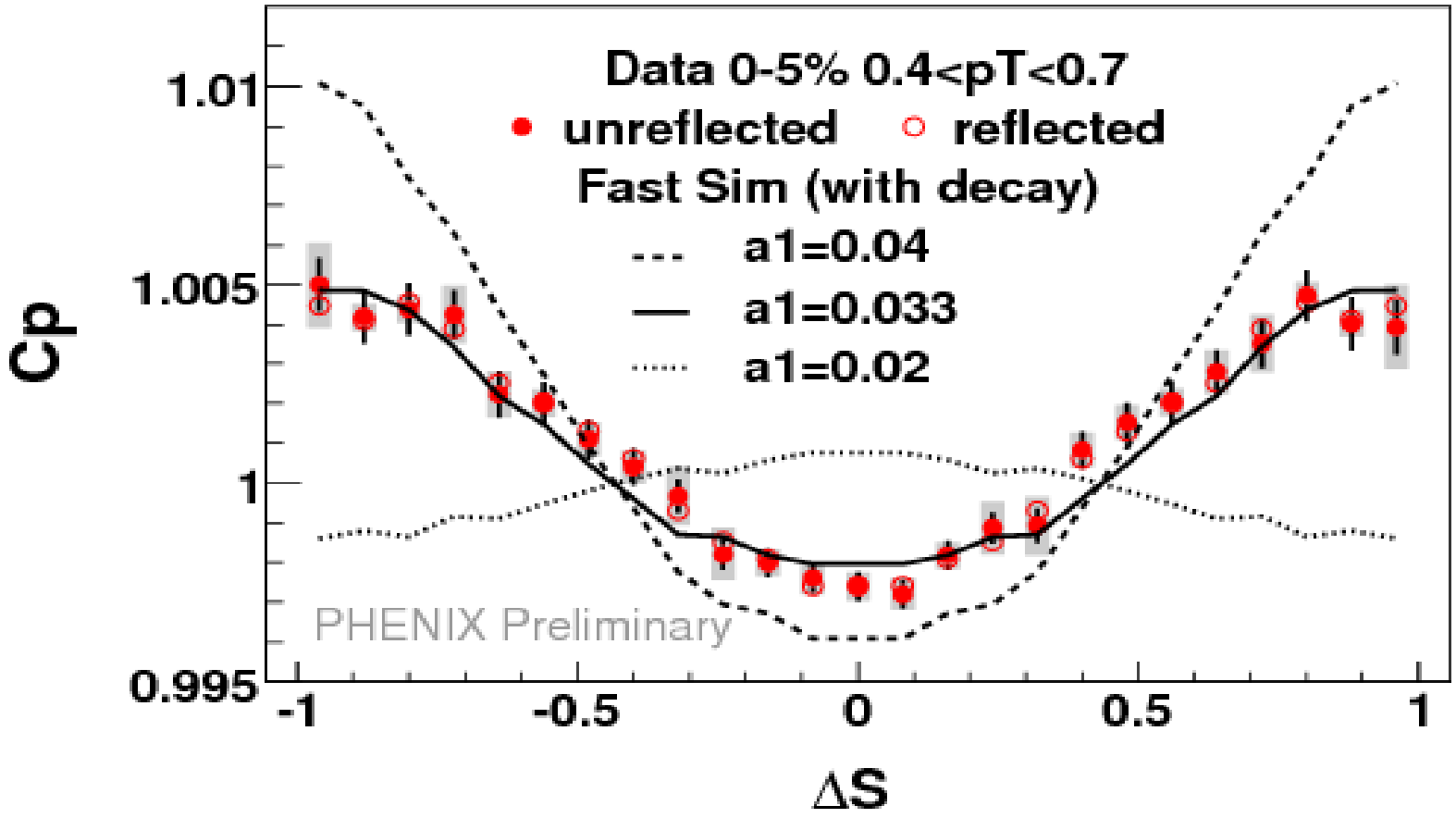
Concave response to "LPV"

Flow : Yes
Parity violating signal : No
Decay : Yes

Convex response to decays



Multi-particle correlation Results



Concave shape validates charge asymmetry w.r.t the reaction plane

→ Note the centrality dependence

Future Studies

- ✓ *Detailed p_T and Centrality dependence*
- ✓ *Beam energy dependence*
- ✓ *Particle Species dependence*
- ❑ *Neutral particles*
- ❑ *Studies with deformed and near-spherical isobars & Isotopes*

Inclusion of v_1 Reaction plane in analysis

Beam Energy Dependence

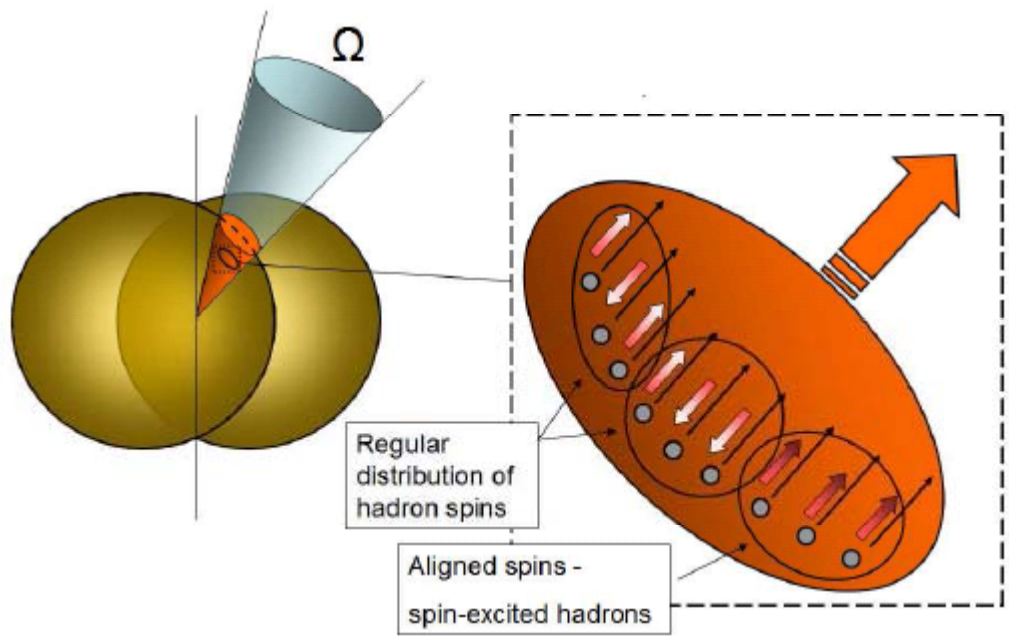
A prerequisite for local parity violation in strongly interacting matter is deconfinement

Low energy scan can offer insights on the onset of deconfinement!

LPV – could serve as an "order parameter" for critical point search

Charge independent Observable

Boaz Keren-Zur and Yaron Oz



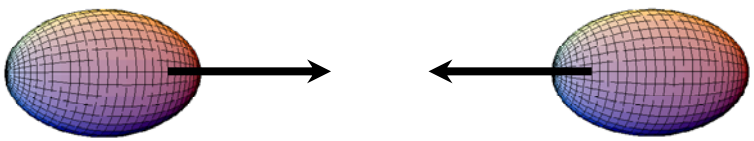
"the axial charge density, in a locally uniform flow of massless fermions, is a measure of the alignment between the fermion spins"

Enhancement of spin-excited hadrons [eg. Ω^-] along the rotation axis!

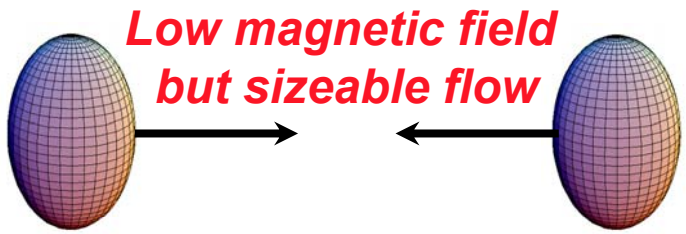
Control the relative importance of B and v_2

Collisions with deformed nuclei

"tip-tip" collision
collision along the longest axis



"body-body" collision
collision along the shortest axis



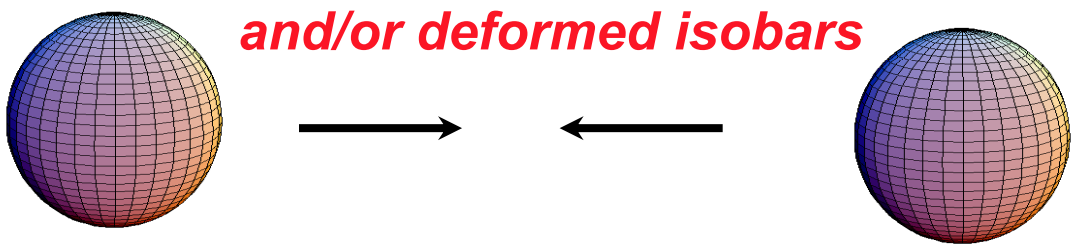
Correlations due to chiral magnetic effect scale with (square of) the magnetic field.

Simulations suggest relatively good separation of collision orientations

Control the Magnitude of B

Correlations due to chiral magnetic effect scale with (square of) the magnetic field.

Collide near-spherical and/or deformed isobars

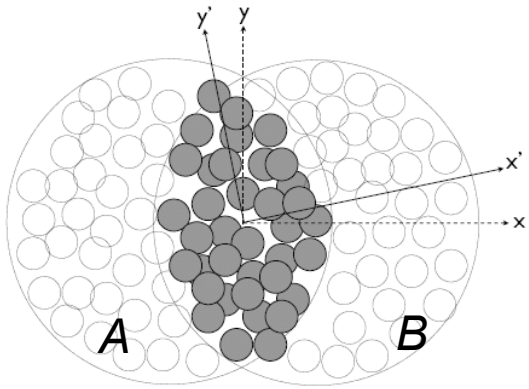


$$^{96}_{44}Ru + ^{96}_{40}Zr$$

$j \sim \mu_5 B$ Kharzeev, Fukushima, Warringa, McLerran...

$j \sim \mu_5 \omega$ chiral rotation effect – D. Son

Collateral Benefit



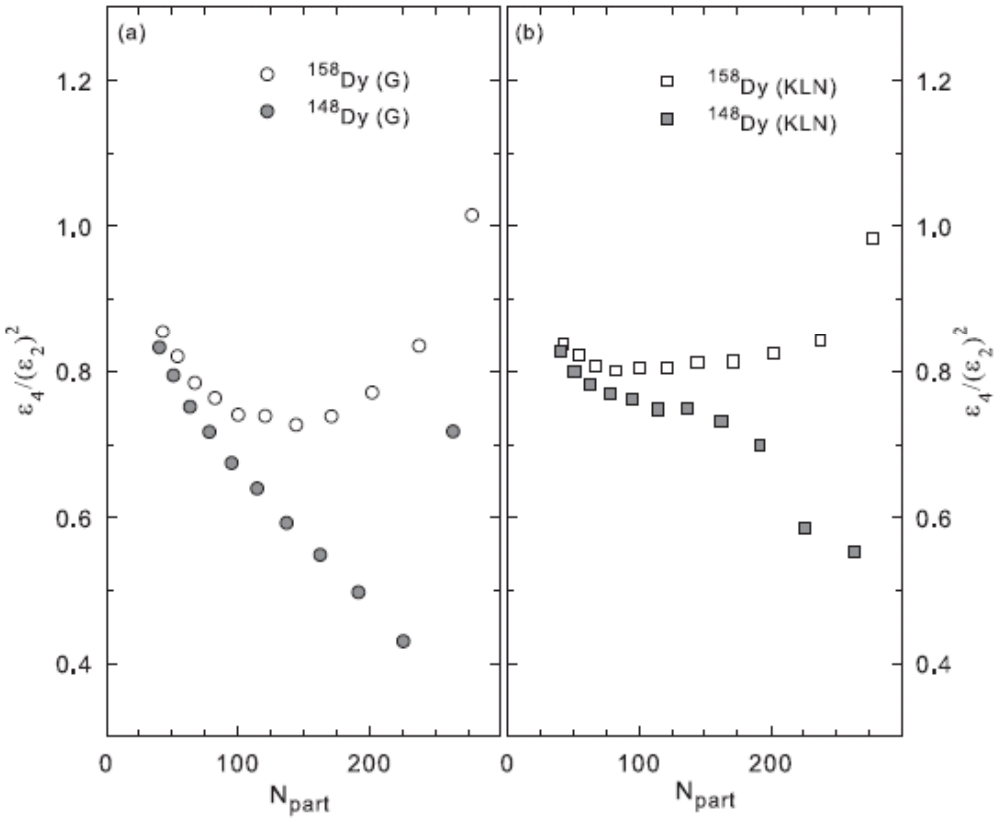
$$S_{nx} \equiv S_n \cos(n\Psi_n^*) = \int d\mathbf{r}_\perp \rho_s(\mathbf{r}_\perp)\omega(\mathbf{r}_\perp)\cos(n\phi)$$

$$S_{ny} \equiv S_n \sin(n\Psi_n^*) = \int d\mathbf{r}_\perp \rho_s(\mathbf{r}_\perp)\omega(\mathbf{r}_\perp)\sin(n\phi),$$

$$\Psi_n^* = \frac{1}{n}\tan^{-1}\left(\frac{S_{ny}}{S_{nx}}\right)$$

$$\varepsilon_2 = \langle \cos 2(\phi - \Psi_2^*)\rangle$$

$$\varepsilon_4 = \langle \cos 4(\phi - \Psi_2^*)\rangle$$

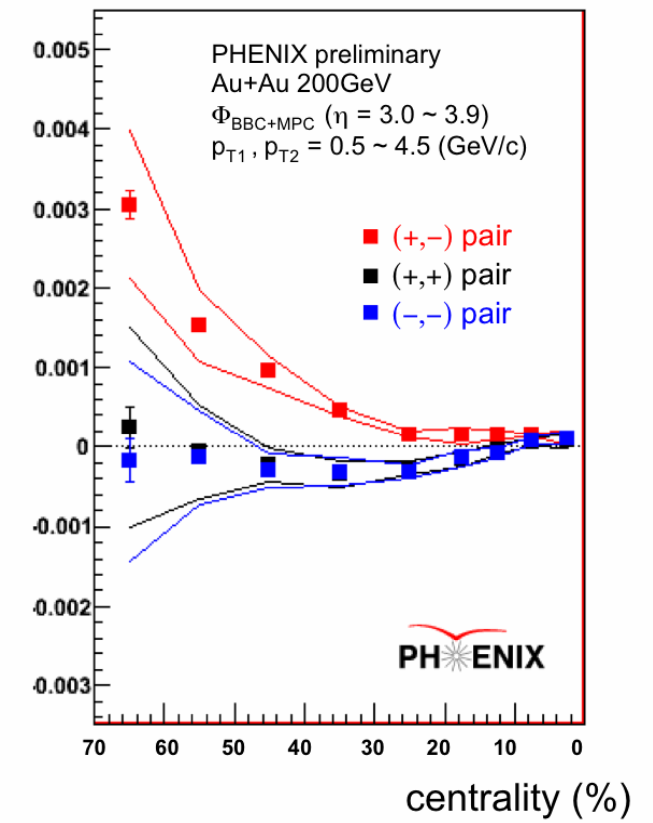


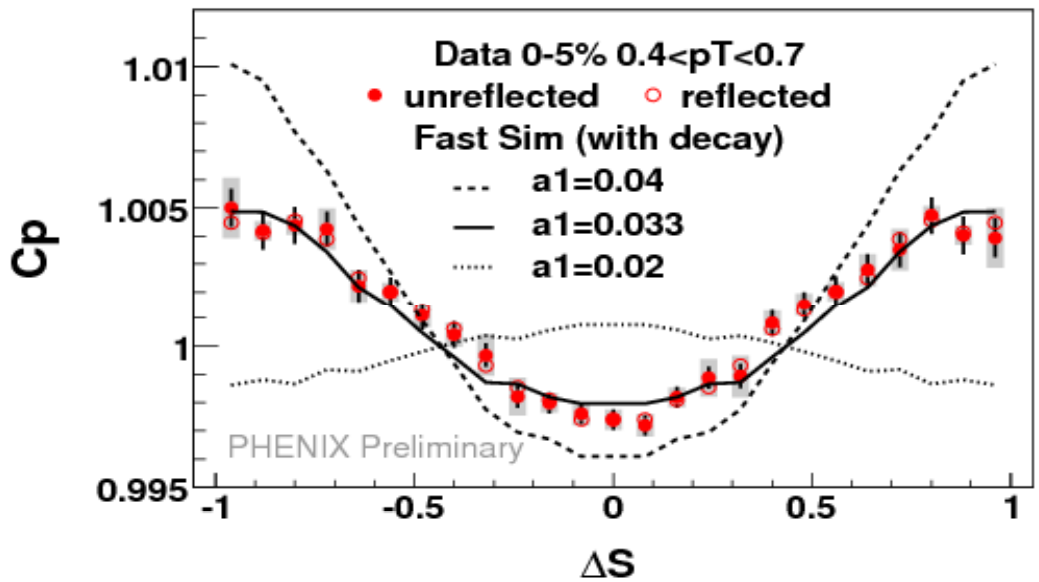
New experimental constraint for Distinguishing Glauber and CGC Initial geometries

Summary

Azimuthal charge-asymmetry measurements are very well launched.

- **Charge-asymmetry observed..**





- **Much work remains – but the stakes are high**