Azimuthal Charge-asymmetry Measurements @ RHIC "a la PHENIX "

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✓3:10 S. Voloshin	Results from STAR
4:00 S. Esumi N. Ajitanand	Results from PHENIX

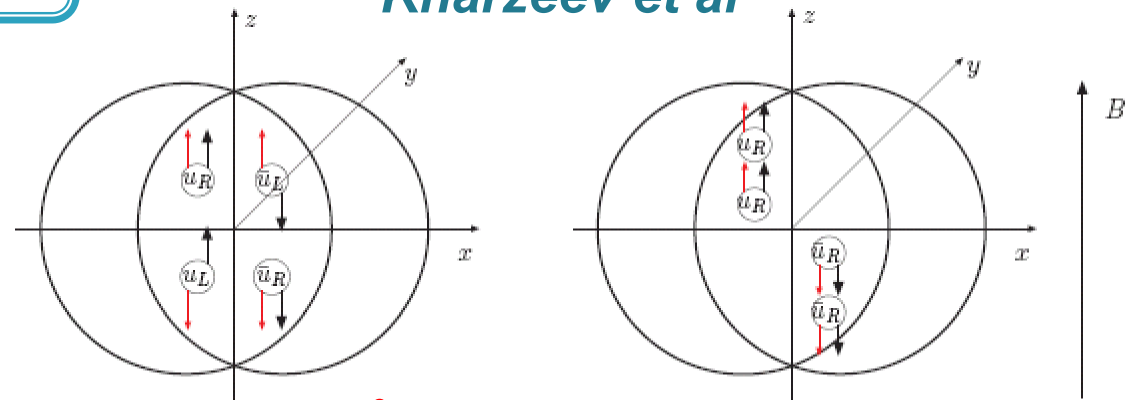
Task

1. *Outline the methodology employed by PHENIX for azimuthal charge asymmetry studies*
2. *Give a survey of current PHENIX results from two very different analysis techniques*
   - *the two particle correlation technique*
   - *the multi-particle correlation technique (New)*
3. *Compare to STAR results where possible*

The Central Question

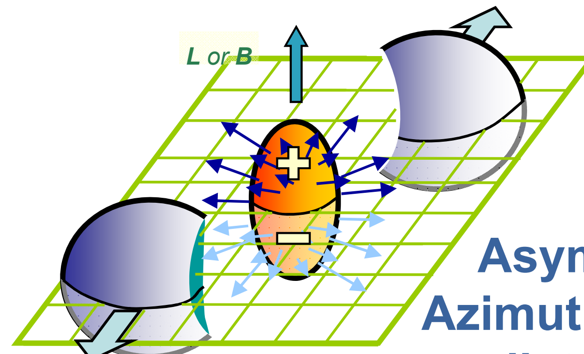
Chiral magnetic effect
Kharzeev et al

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



Chiral chemical potential -> $\mu_5 = 0$ $\mu_5 \neq 0$

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

Why study *Azimuthal Charge-asymmetry*?

Unambiguous experimental observations of the chiral magnetic effect would be 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]

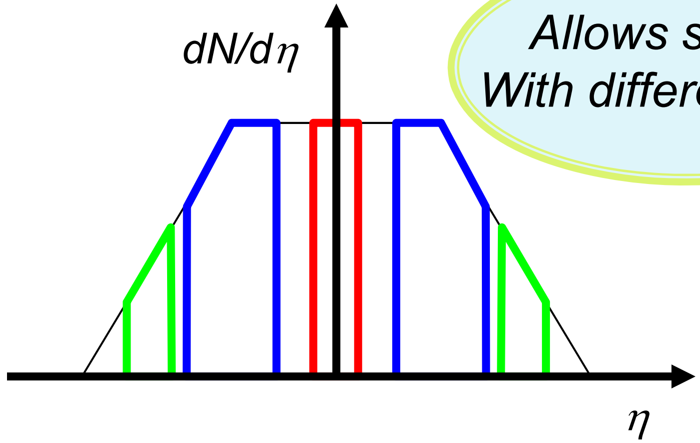
Azimuthal charge-asymmetry studies could also be an indispensable tool for further insights on deconfinement [and chiral symmetry restoration]

Azimuthal Charge-asymmetry Studies in PHENIX

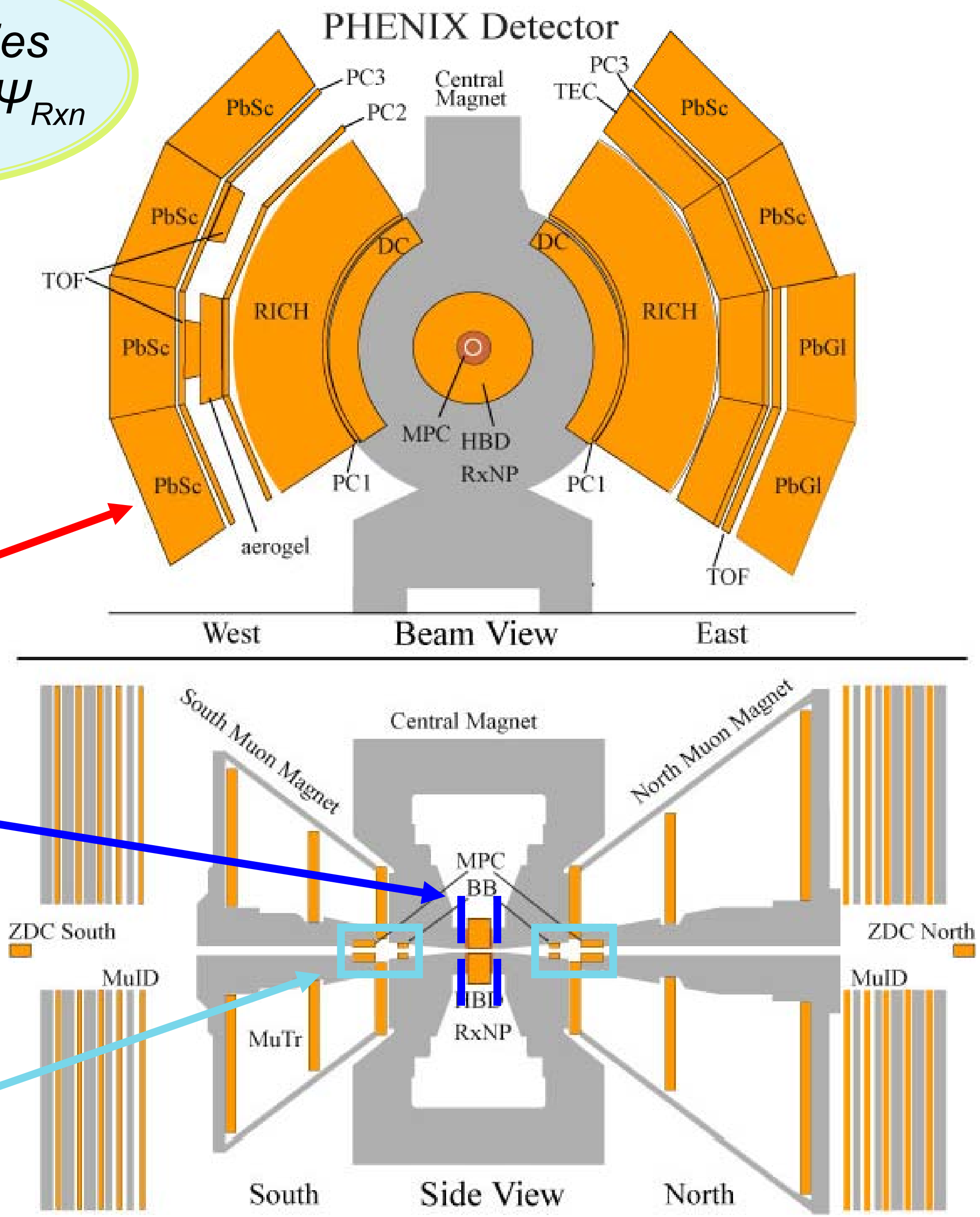
Two-article correlation measurements relative to the reaction plane
ShinIchi Esumi

Multi-particle correlation measurements relative to the reaction plane
N. Ajitanand

Correlation measurements are important due to the PHENIX acceptance



Allows studies
With different Ψ_{Rxn}



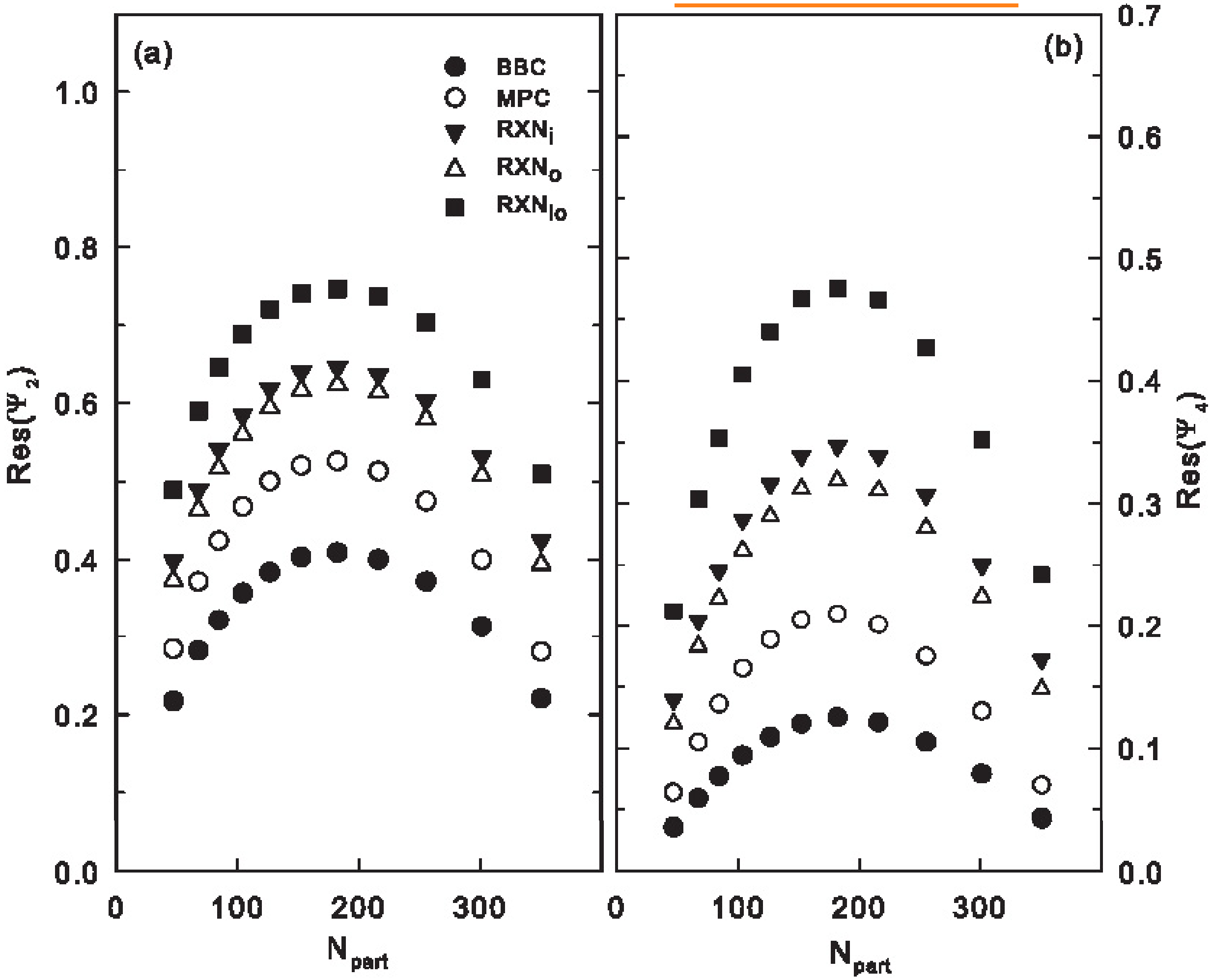
Charged Particle Tracks
$|\eta|<0.35$, $\pi/2$ x 2 arms
Central Arm Spectrometer (DC,PCs)

Mid Reaction Plane
$1.0<|\eta|<2.8$, $0<\varphi<2\pi$
Reaction Plane Detector (RXN)

Forward Reaction Plane
$3.0<|\eta|<3.8$, $0<\varphi<2\pi$
Beam Beam Counter (BBC)
Muon Piston Calorimeter (MPC)

Reaction Plane

PHENIX arXiv:1003.5586



Event planes

$$3.1 < |\eta_{BBC}| < 3.9$$

$$3.1 < |\eta_{MPC}| \lesssim 3.9$$

$$1.5 < |\eta_{RXN_i}| < 2.8$$

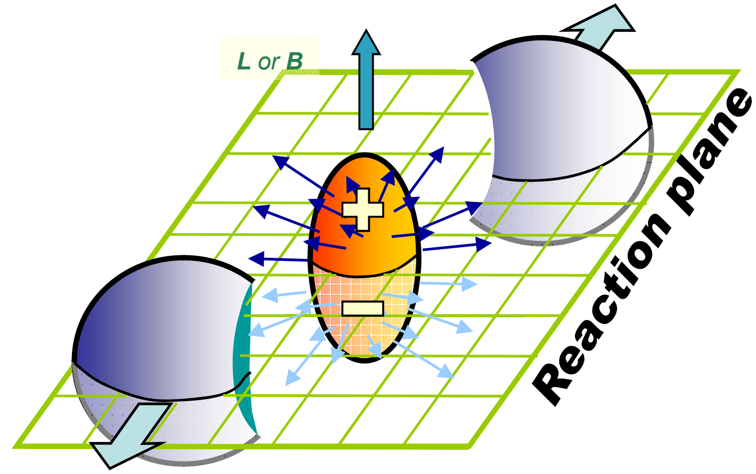
$$1.0 < |\eta_{RXNo}| < 1.5$$

$$1.0 < |\eta_{RXN_{io}}| < 2.8$$

Significant benefits derived from the new Reaction Plane Detector (RXN)

The two-particle correlation probe

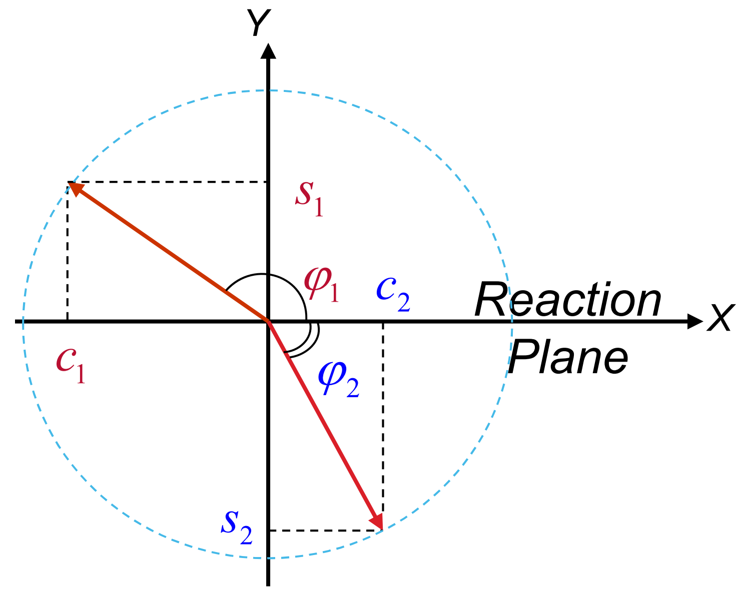
Two-particle correlation Probe



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

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

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

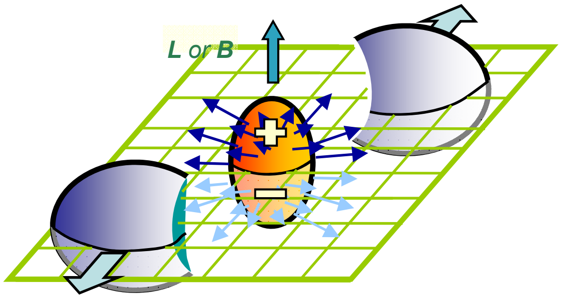


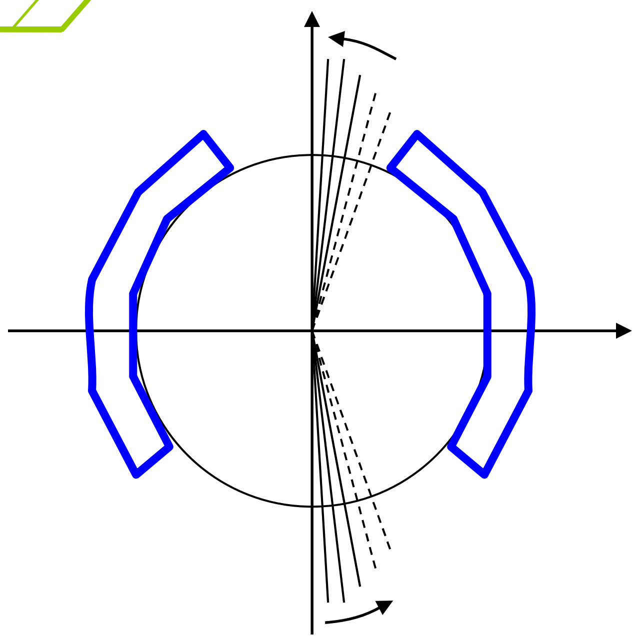
Averaging is performed over all pairs in a given event and then over all events with a given centrality

✓acceptance correction accounted for with event mixing

✓reaction plane resolution correction

Two-particle correlation Probe





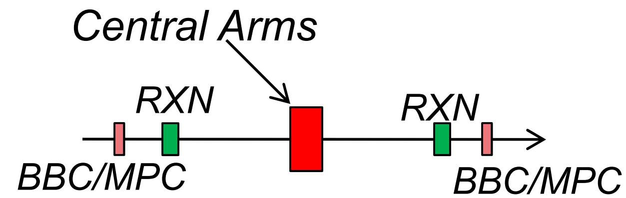
Technical details for experimentalists

- ✓ *Event mixing in centrality: 10 bins [0-100%] z-vertex: 10 bins [-30~30cm] reaction plane: 50 bins [$-\pi/2\sim\pi/2$]*
- ✓ *Mixed event within the same event class of (cent, z-vtx, R.P.) in order to take into account the acceptance as well as residual flow effects to be removed.*
- ✓ *Measure $F_{AB}=\langle\cos(\phi_A+\phi_B-2\Phi_{R.P.})\rangle$ and for F_{+-}, F_{++} and F_{--} for both real and mixed events*
- ✓ *Take a difference between real and mixed, then correct for R.P. resolution: $(F_{real}-F_{mixed}) / Res_{R.P.}$*

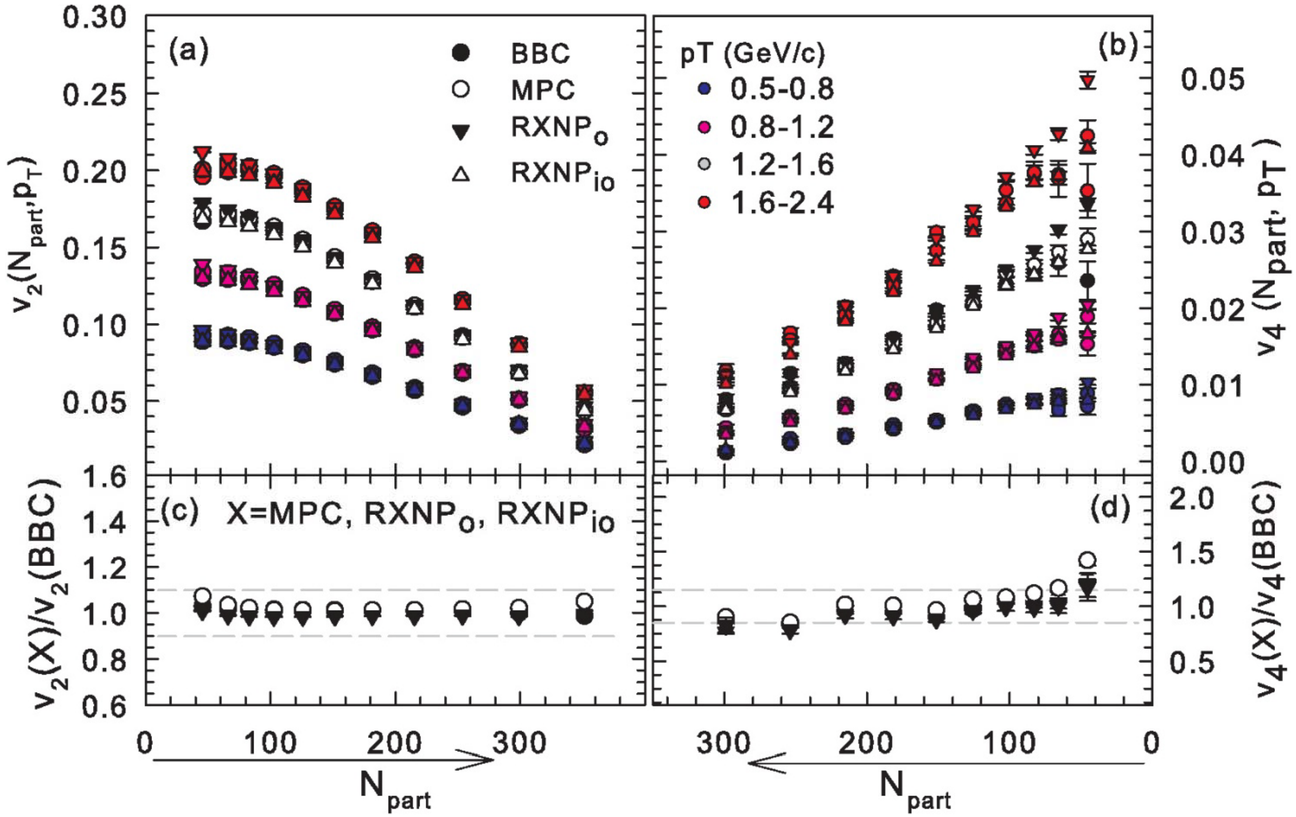
The precision of these measurements is crucial!

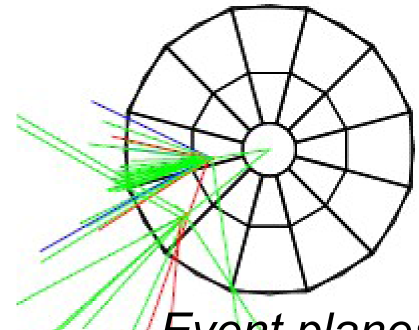
Both single and two particle Measurements carefully checked!

Single particle Flow measurements are robust



PHENIX arXiv:1003.5586





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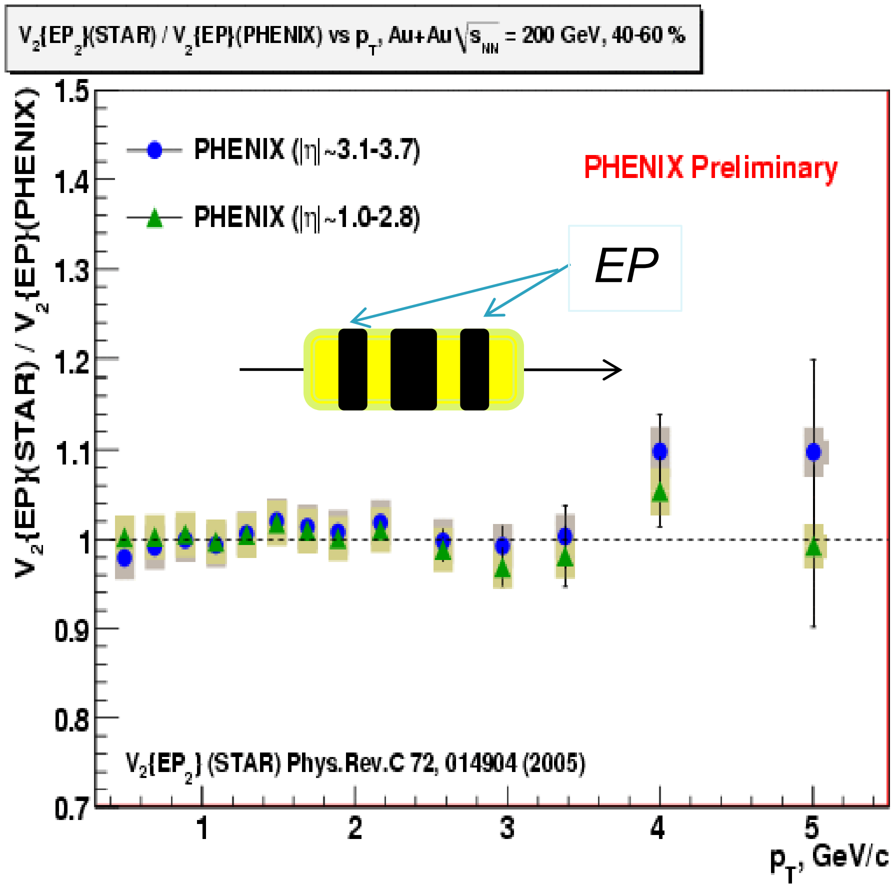
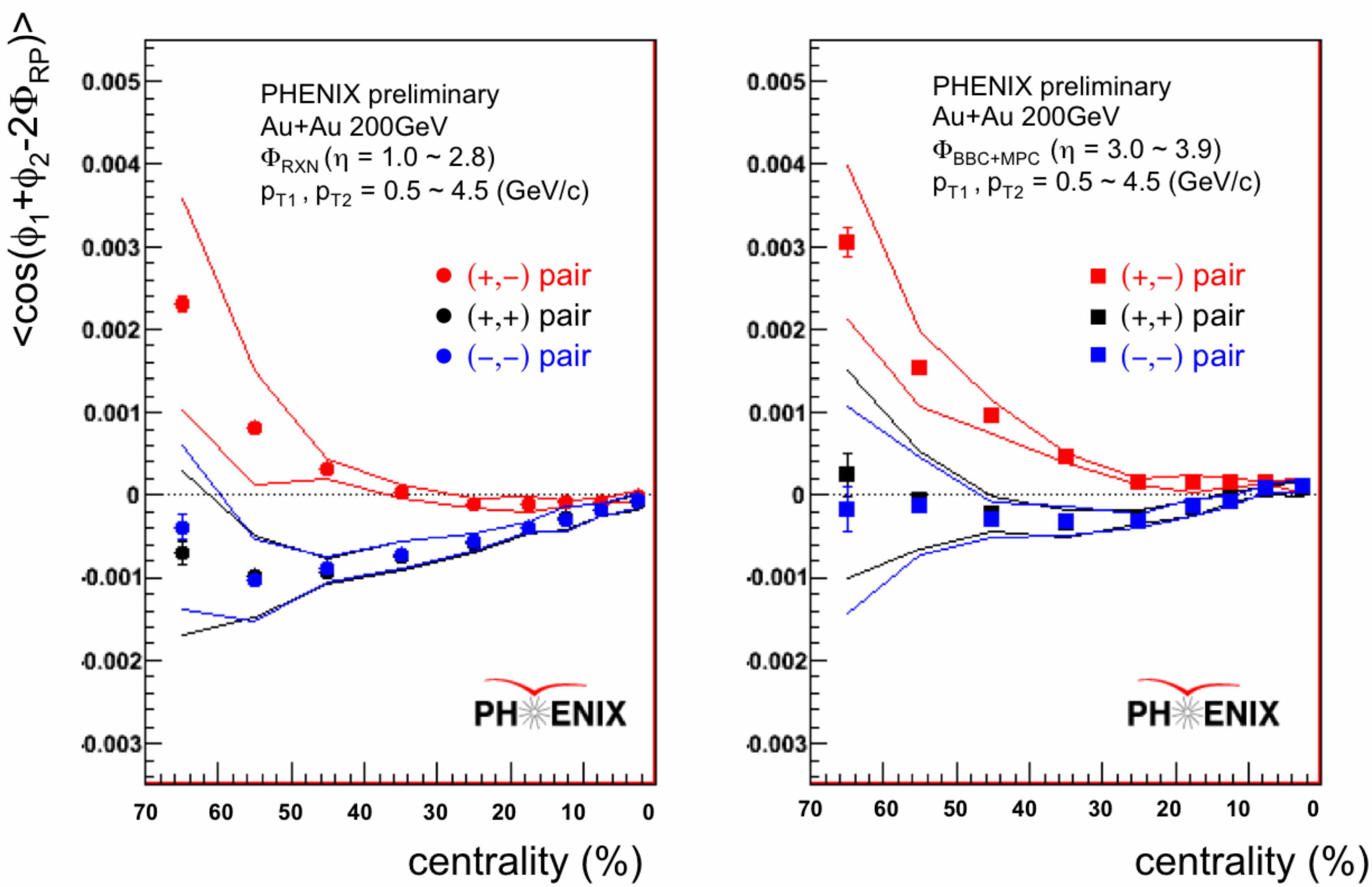
➢ *No evidence for significant η-dependent non-flow contributions*

Single particle Flow measurements are robust



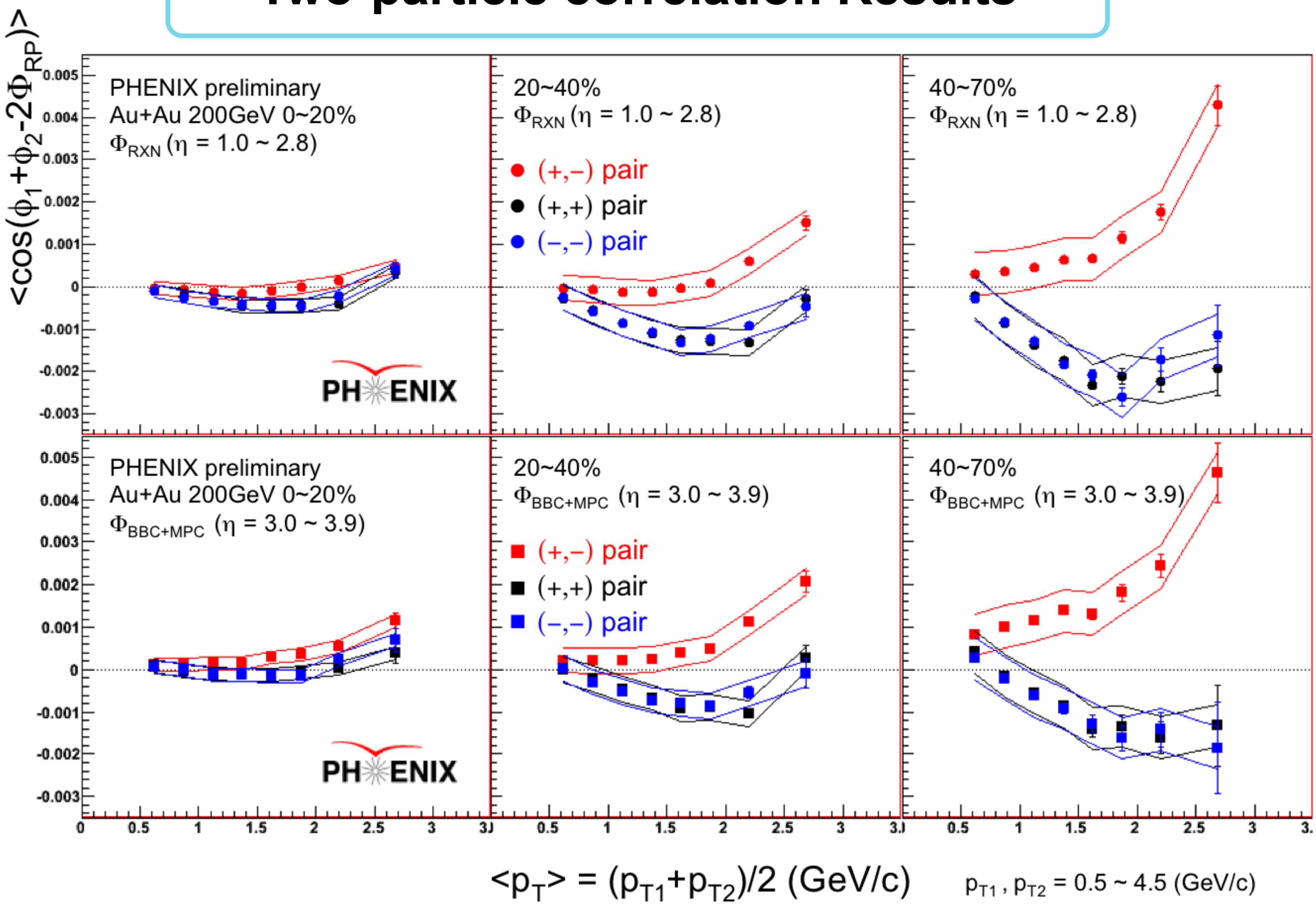
Results from different event planes show good agreement

Two-particle correlation Results



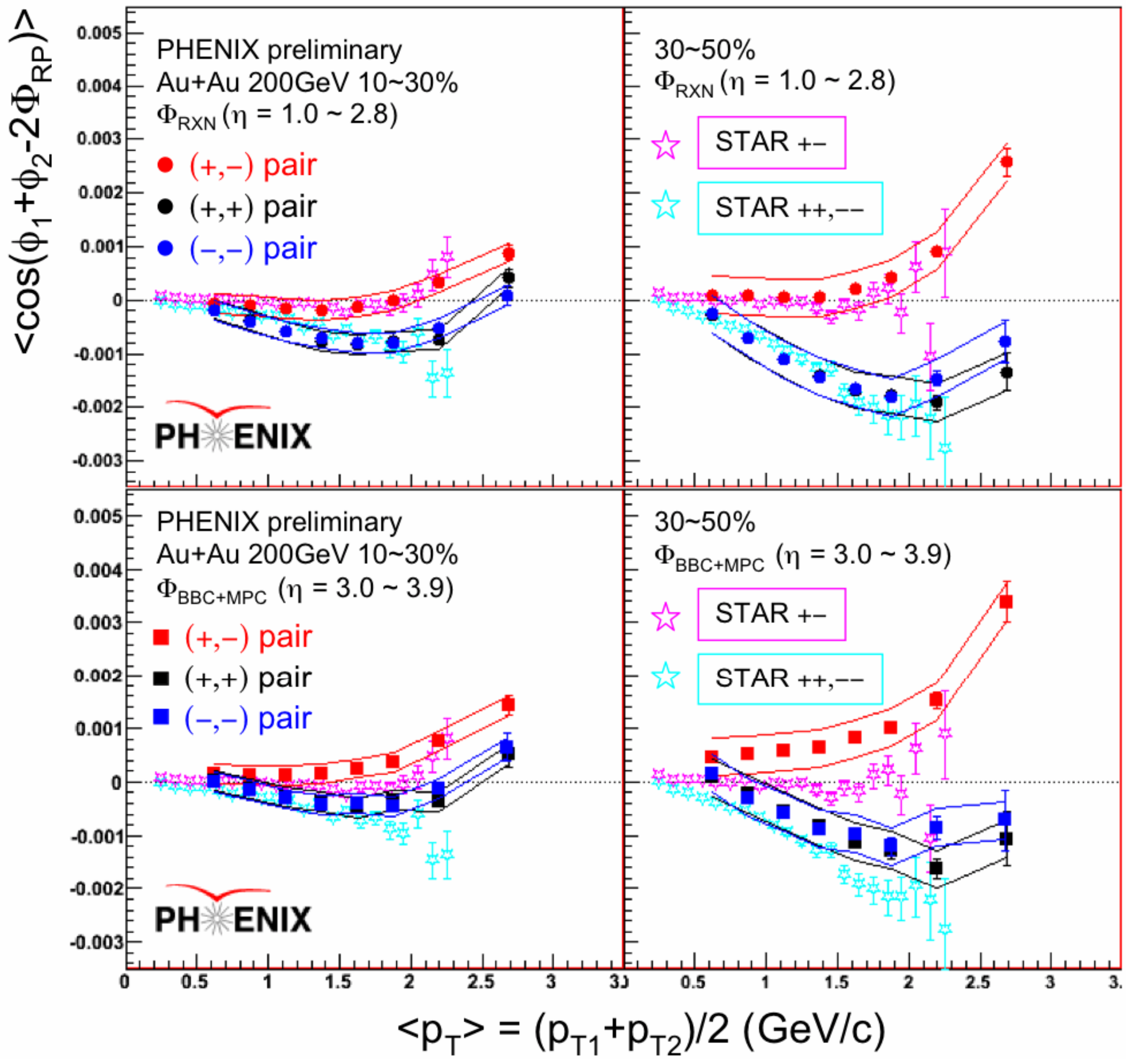
Signal is sensitive to collision centrality

Two-particle correlation Results



Signal grows with centrality and p_T

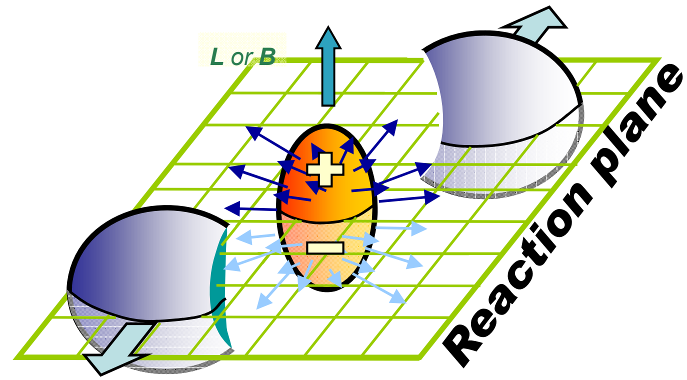
Two-particle correlation Results



Relatively good agreement between PHENIX & STAR

The multi-particle correlation probe

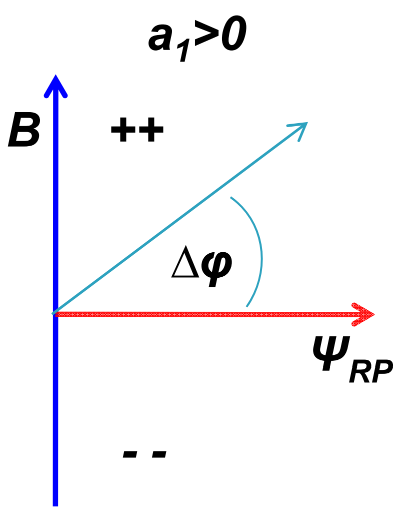
Mult-particle correlation probe



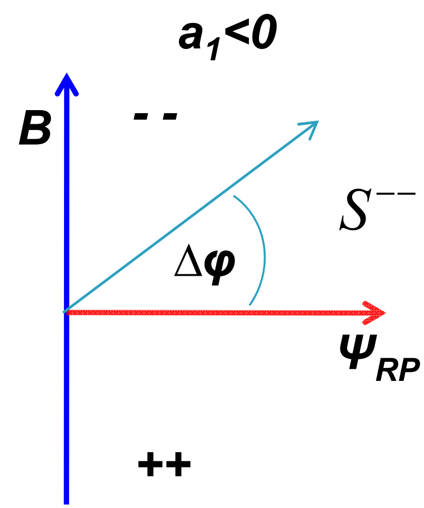
Charge sensitive correlation function

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

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



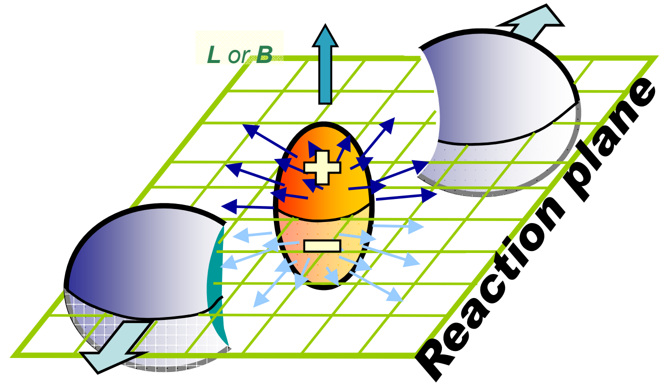
Positive charge favor B



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

Negative charge favor B

Mult-particle correlation probe



$$S = \sin(\Delta\varphi)$$

Consider an event of multiplicity M having p positively charged hadrons and n negatively charged hadrons i.e. M = p + n

$\left\langle S_p^{h+} \right\rangle$ ***average over the p positively charged hadrons in the event***

$\left\langle S_n^{h-} \right\rangle$ ***average over the n negatively charged hadrons in the event***

$\left\langle S_p^{h\mp} \right\rangle$ ***average over p randomly chosen hadrons in the same event***

$\left\langle S_n^{h\mp} \right\rangle$ ***average over the remaining n hadrons in same event***

$$C_{\mathrm{p}}(\Delta S) = \frac{N\left(\left\langle S_p^{h+} \right\rangle - \left\langle S_n^{h-} \right\rangle\right)}{N\left(\left\langle S_p^{h\mp} \right\rangle - \left\langle S_n^{h\mp} \right\rangle\right)}, \quad \Delta S = \left\langle S_p \right\rangle - \left\langle S_n \right\rangle$$

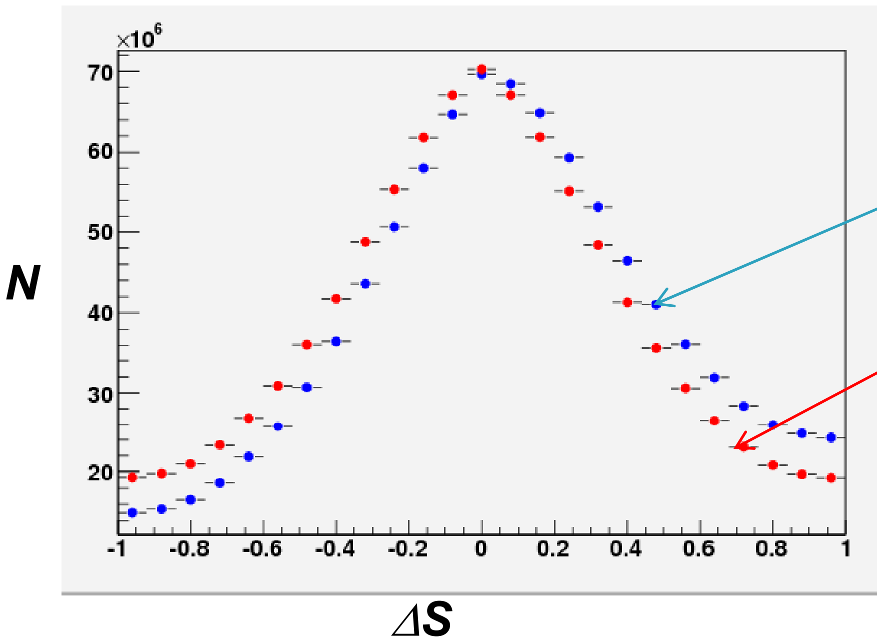
N is the distribution over events

C_p is a charge sensitive correlator

Properties of C_p

Simulated Results

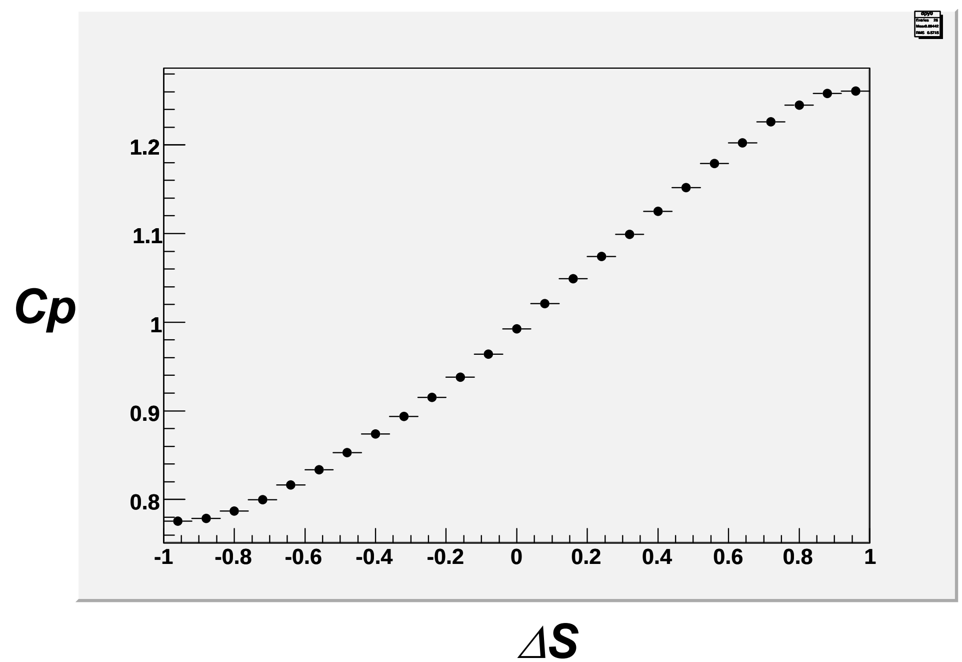
$a_1 > 0$ in all events



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

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

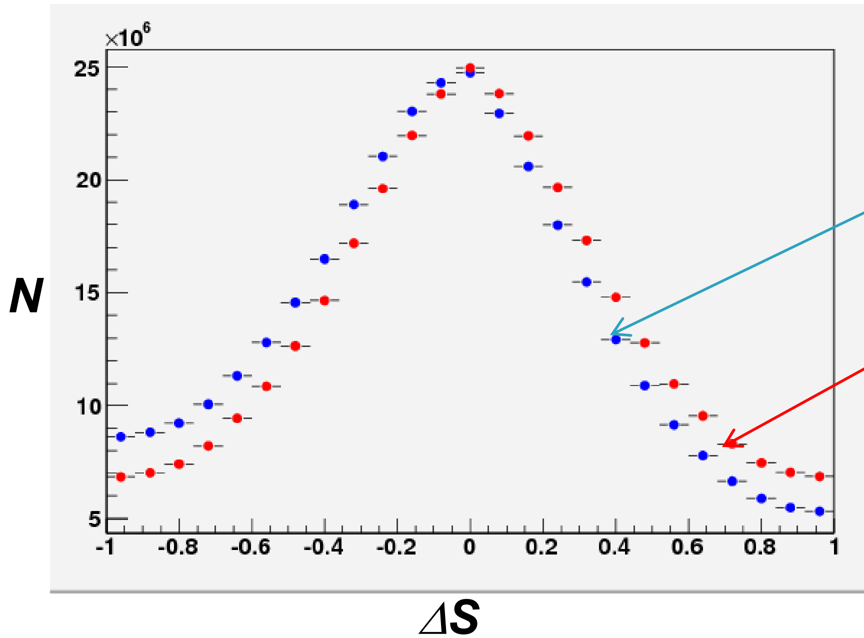
Numerator shifted to the right
C_p shows positive slope



Properties of C_p

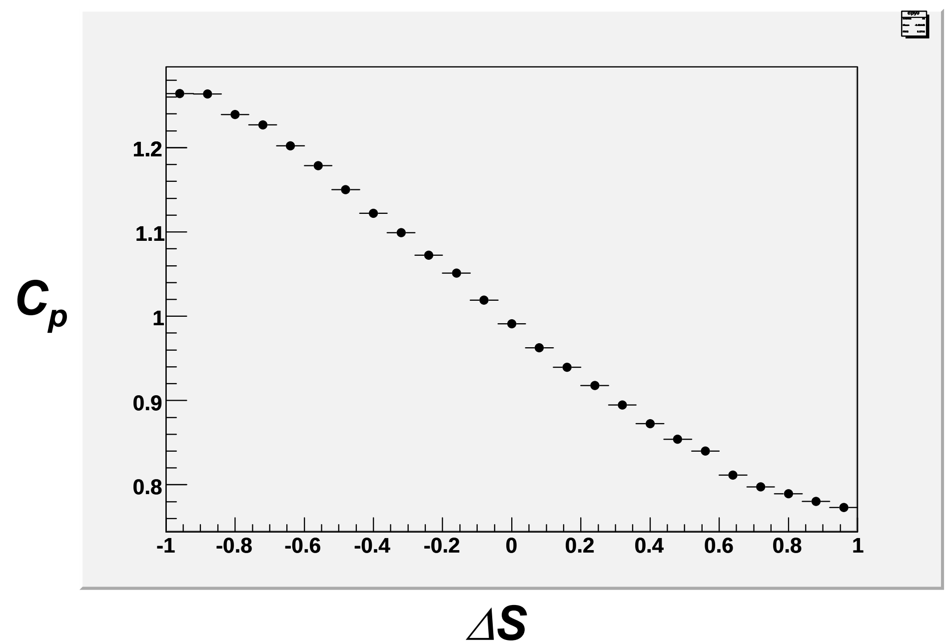
Simulated Results

$a_1 < 0$ in all events



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

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



Numerator shifted to the left

C_p shows negative slope

Properties of C_p

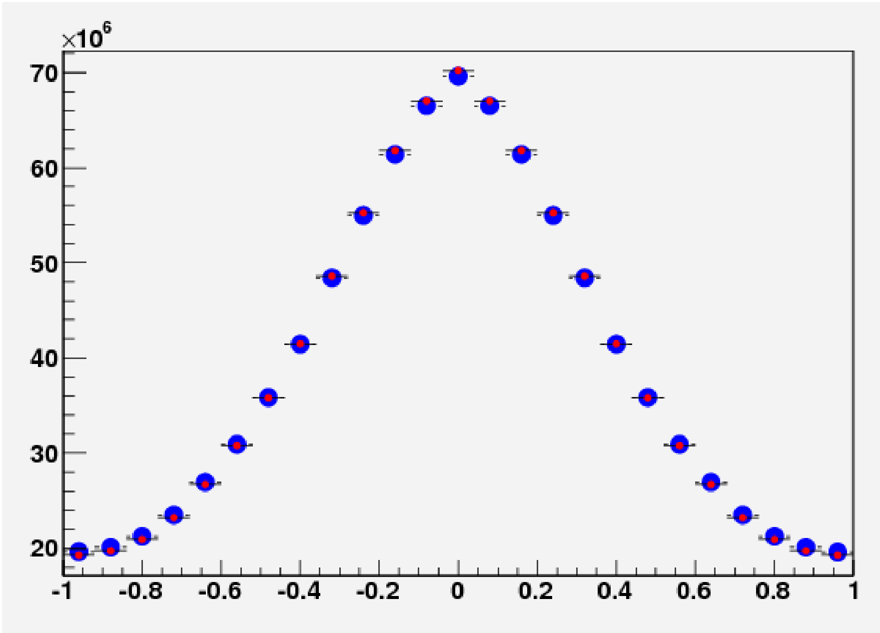
Simulated Results

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)**

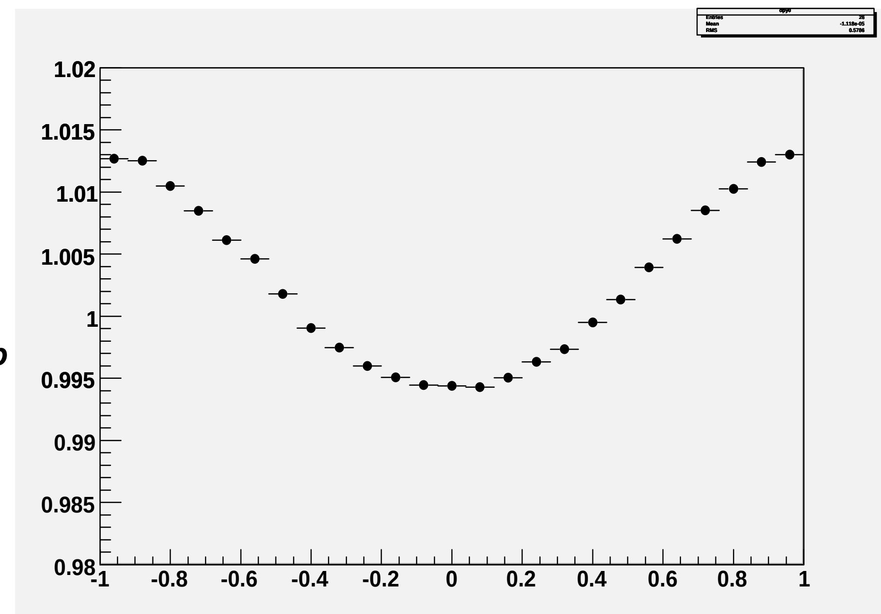
N



ΔS

Numerator slightly broader
C_p concave and symmetric

C_p

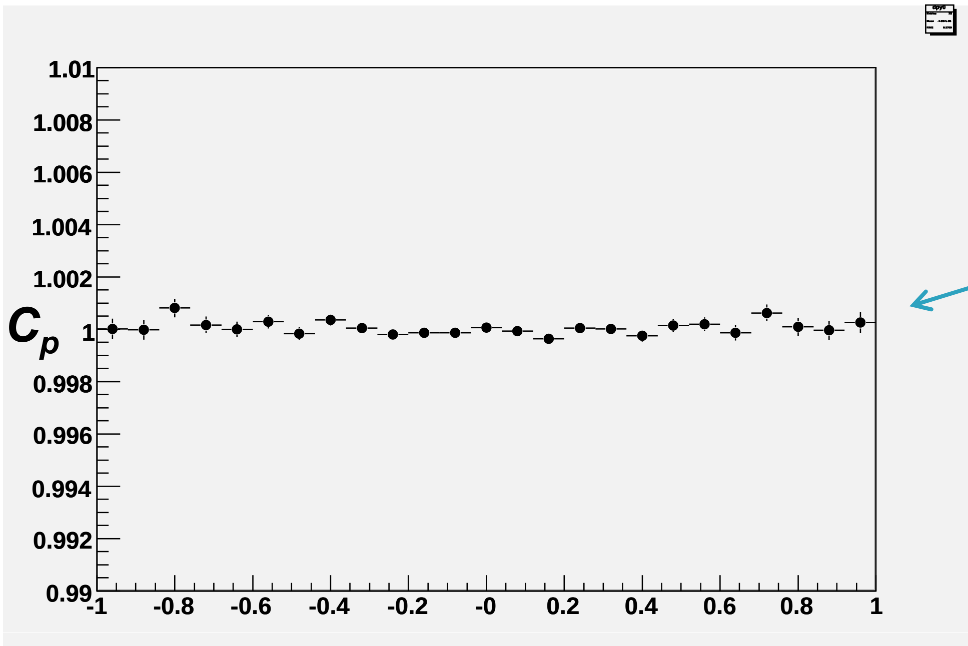


ΔS

Properties of C_p

Simulated Results

C_p is an in-event correlator
→ Several benefits



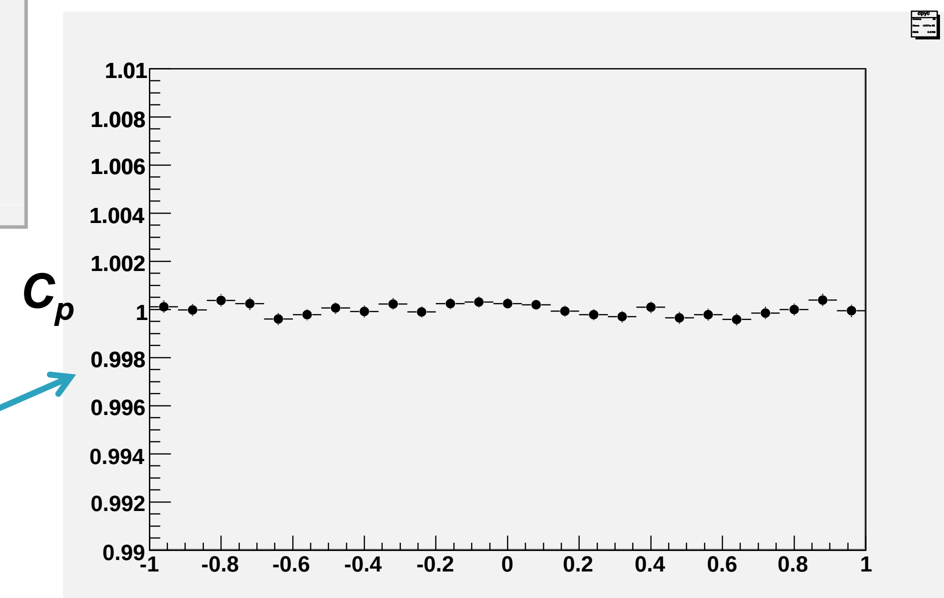
ΔS

Flow : Yes
Parity violating signal : No
Decay : No

Flat response to flow

Jet : Yes
Parity violating signal : No
Decay : No

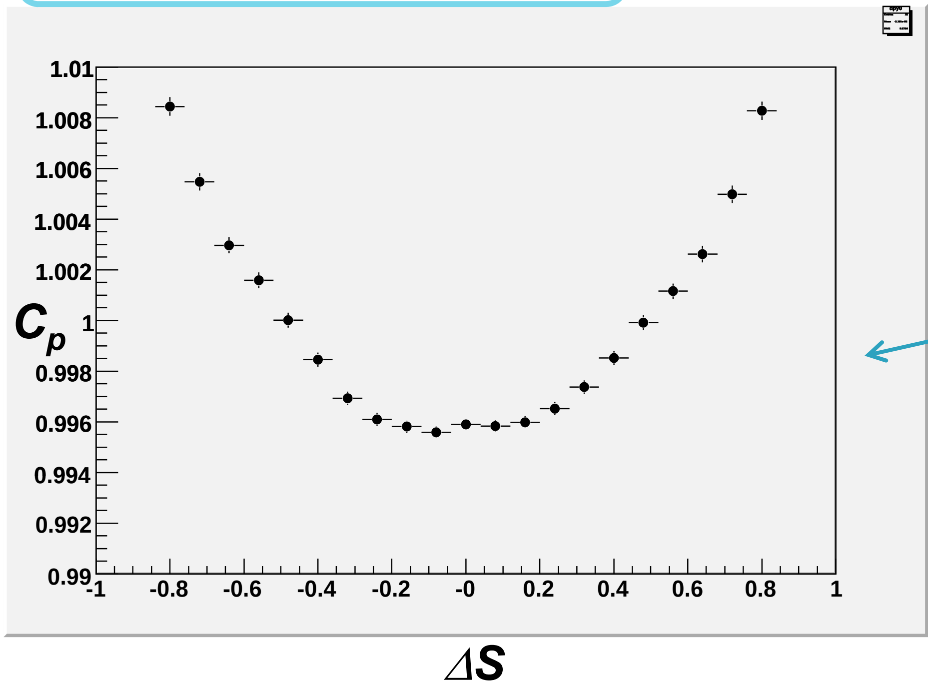
Flat response to jets



ΔS

C_p insensitive to flow and jets

Properties of C_p



Simulated Results

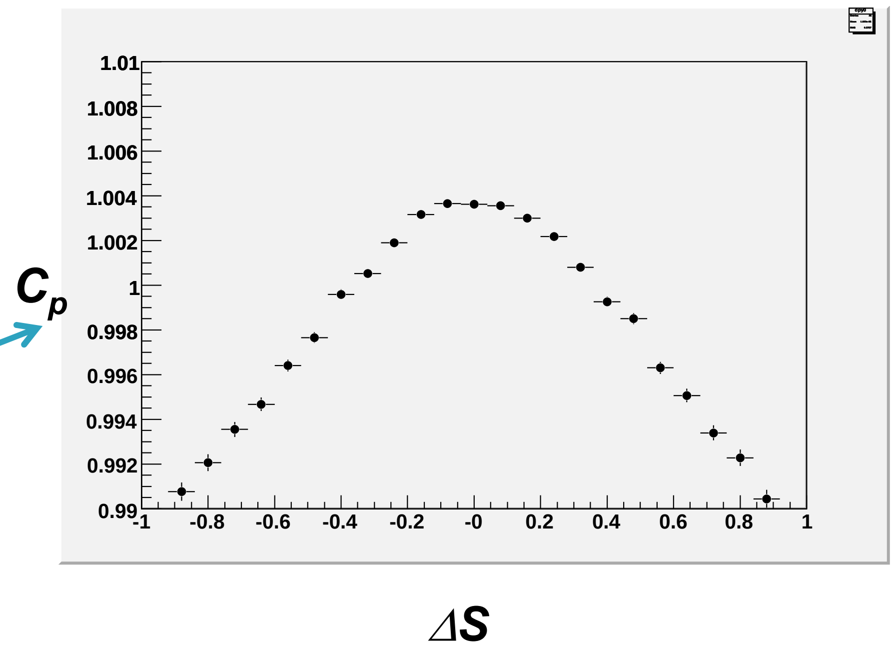
C_p is an in-event correlator
→ Several benefits

Flow : Yes
Parity violating signal : Yes
Decay : No

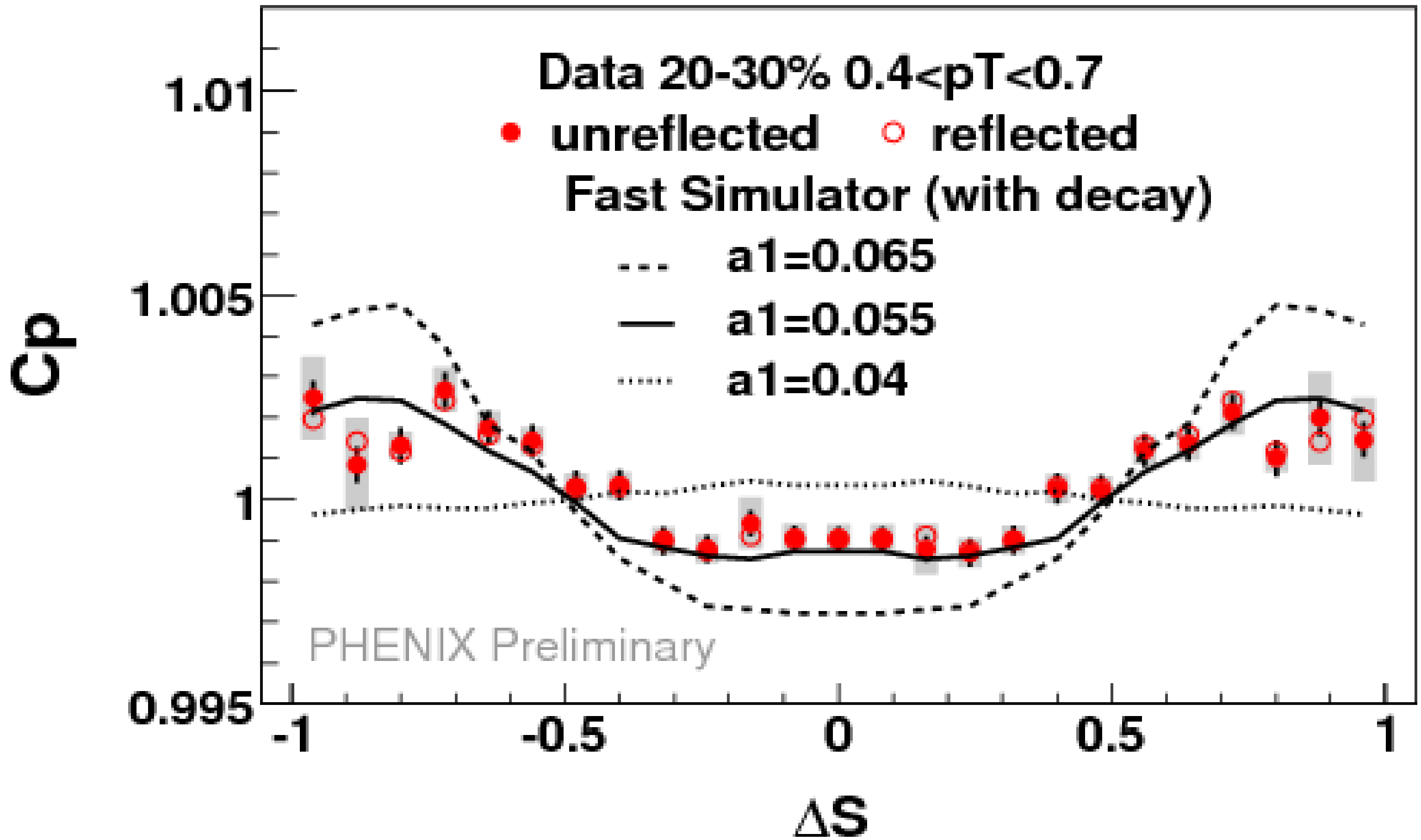
Concave response to parity violation

Flow : Yes
Parity violating signal : No
Decay : Yes

Convex response to decays

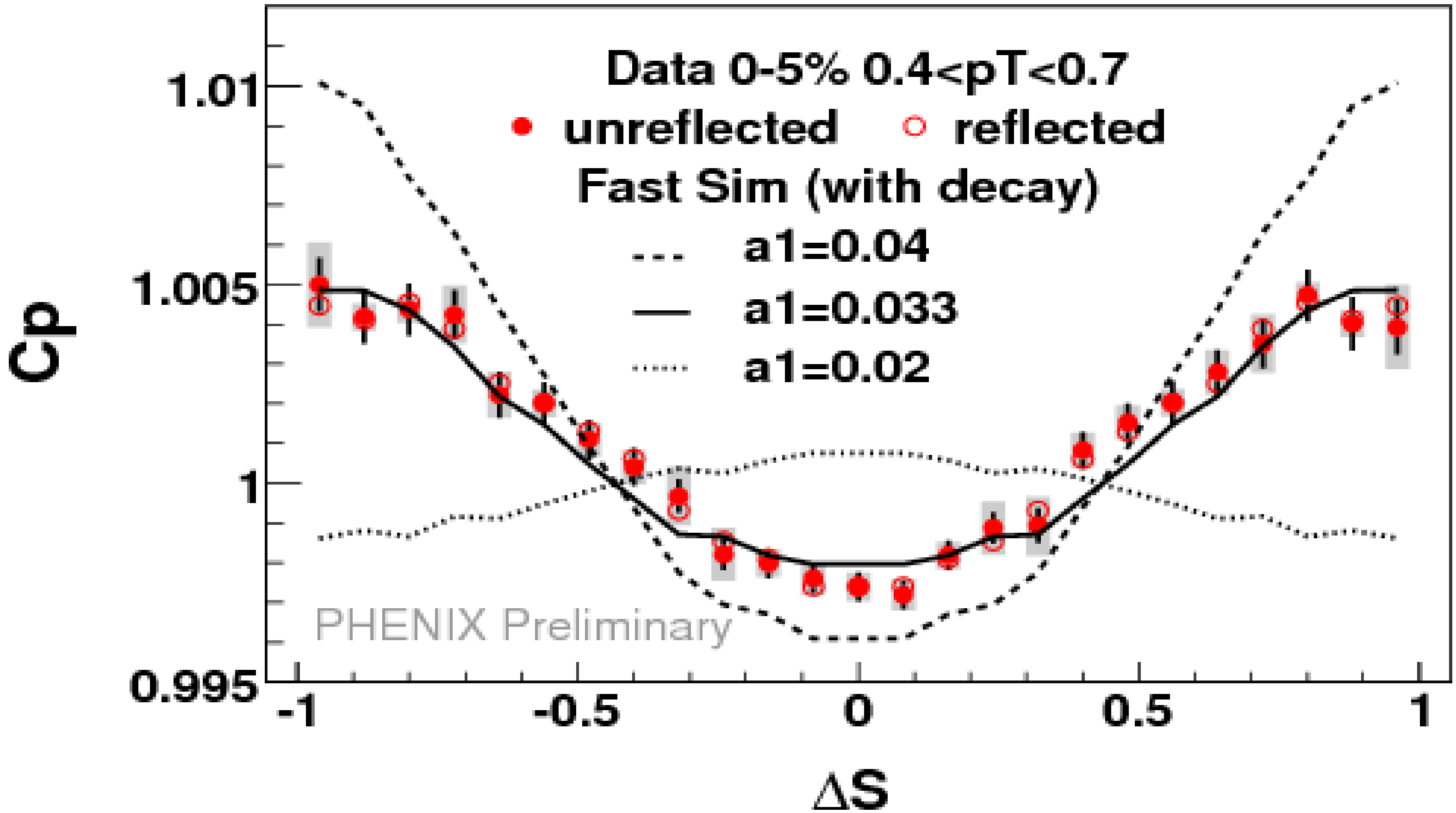


Multi-particle correlation Results



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

Multi-particle correlation Results

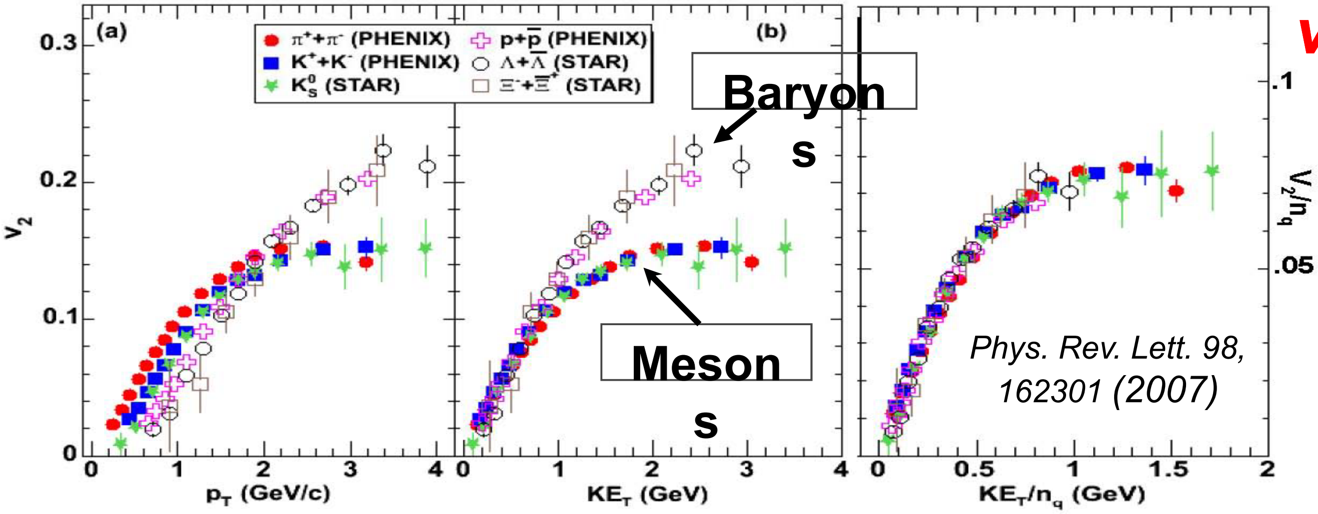


Concave shape validates charge asymmetry w.r.t the reaction plane
→ Note the centrality dependence

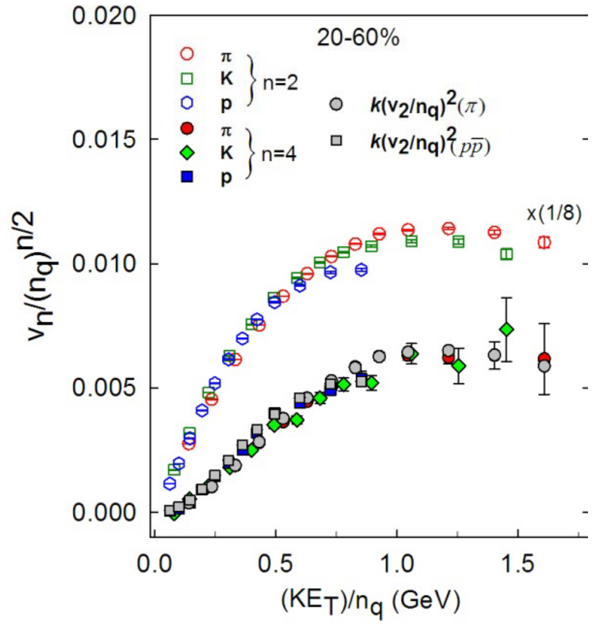
A prerequisite for local parity violation in strongly interacting matter is deconfinement

Any independent evidence for deconfinement ?
Strong coupling?

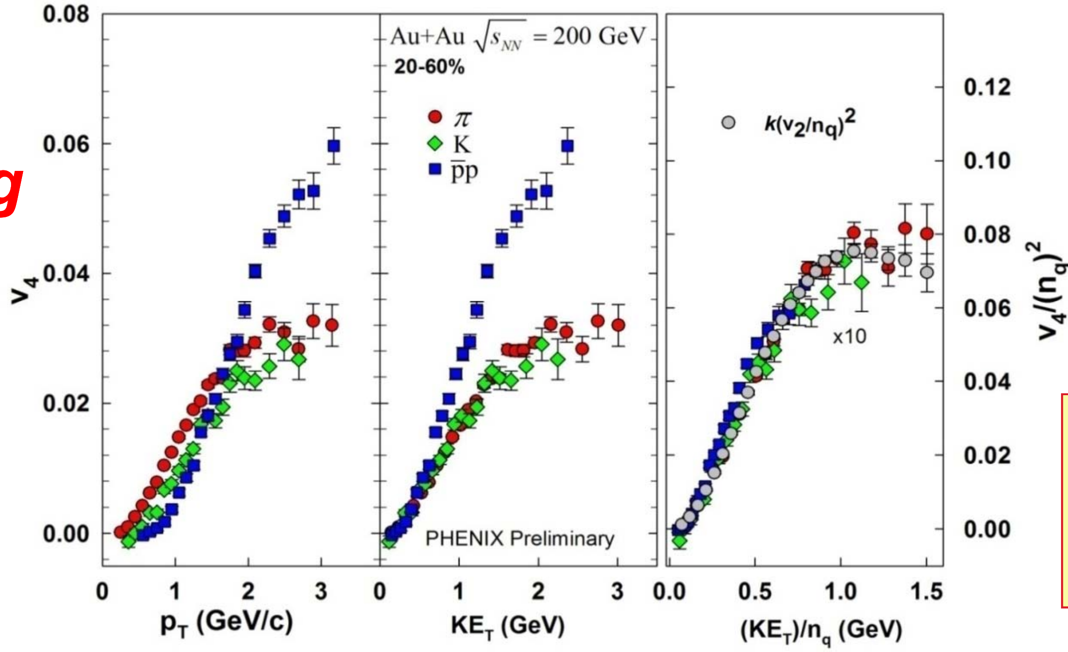
Universal scaling of harmonic flow at RHIC



v_2 scaling



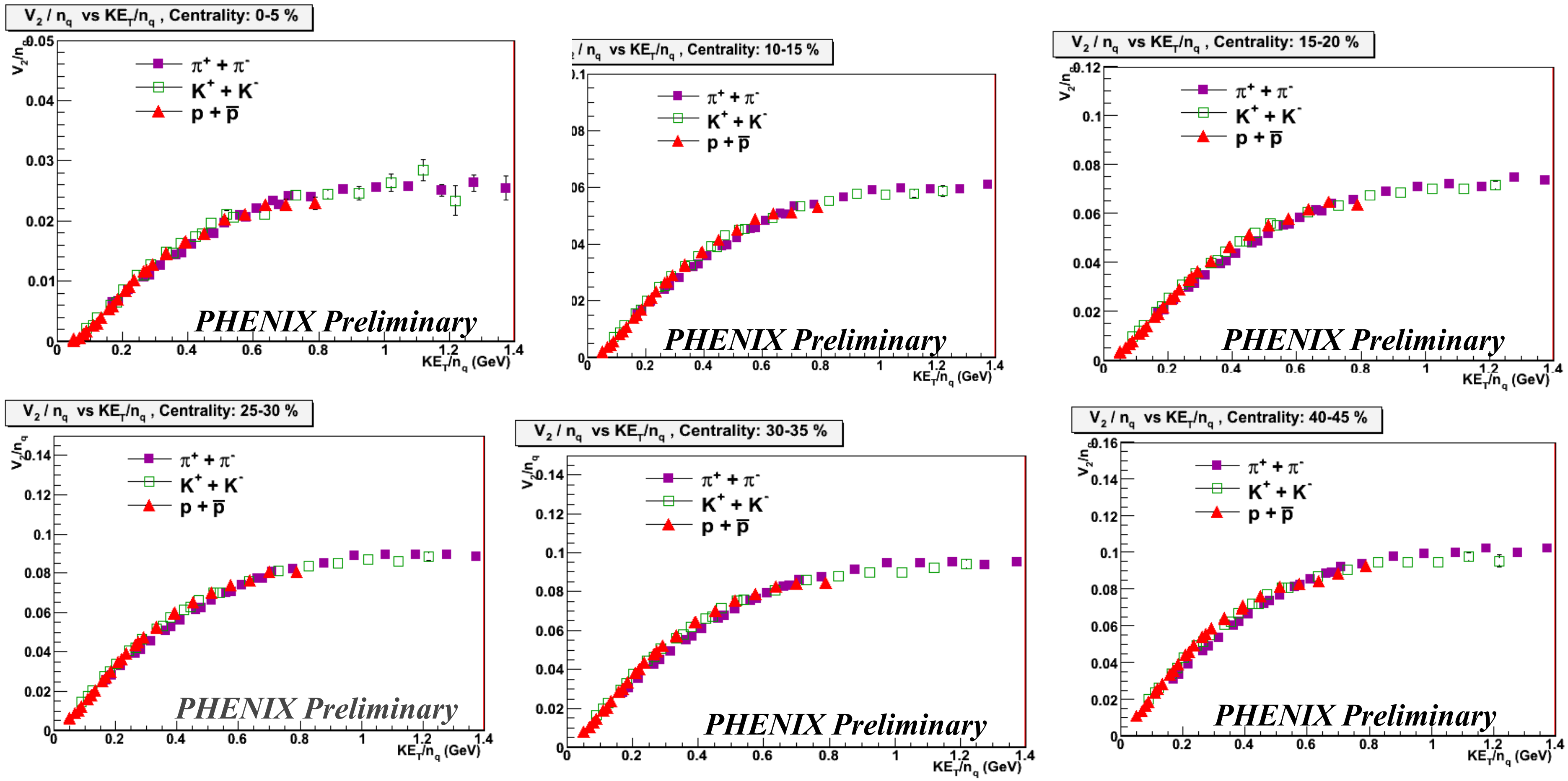
v_4 scaling



Universal scaling

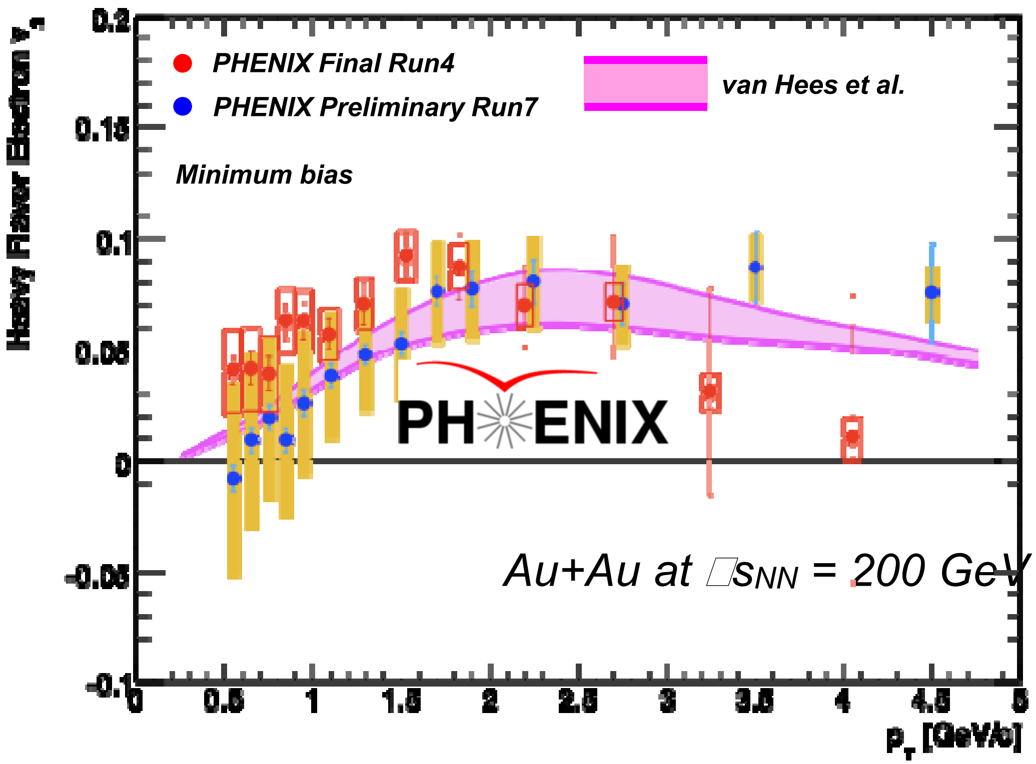
KE_T & n_q (n_q^2) scaling validated for v_2 (v_4)
→ Partonic flow

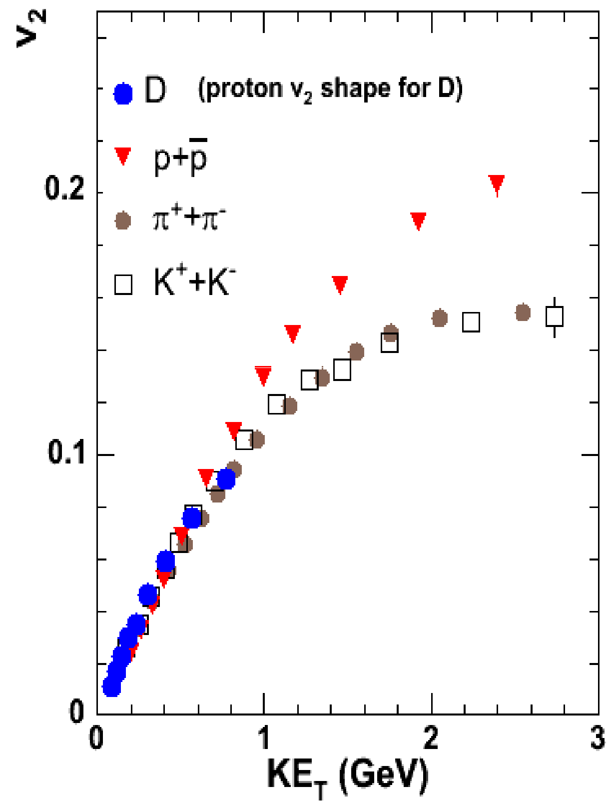
Flow scales across centrality



KE_T & n_q (n_q^2) scaling validated for v_2 as a function of centrality

Charm flows and scales

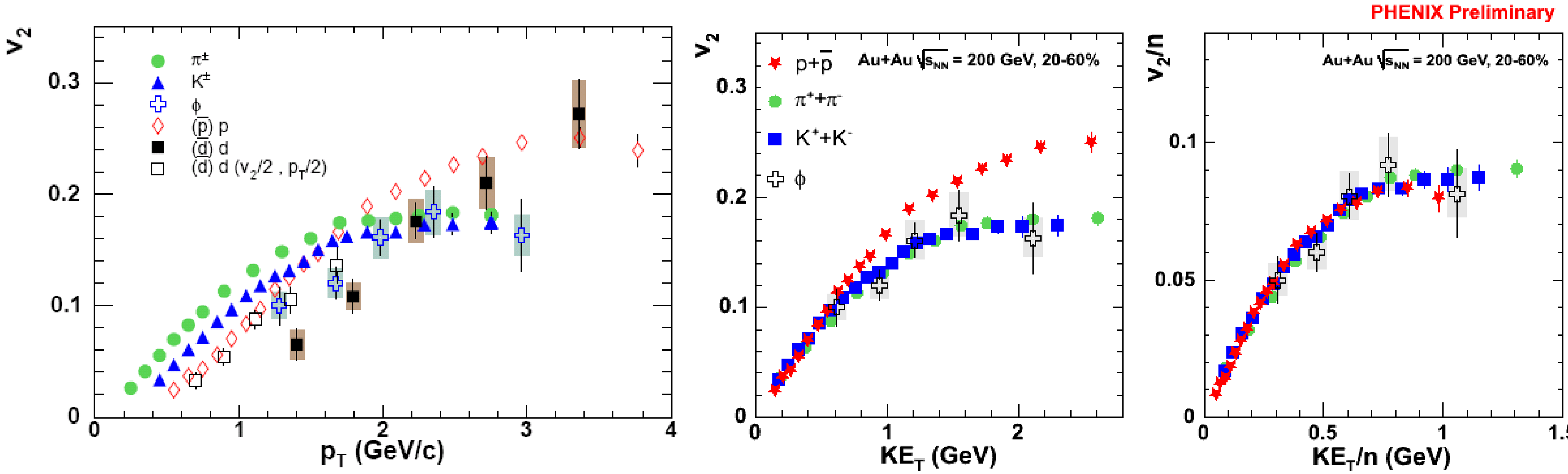




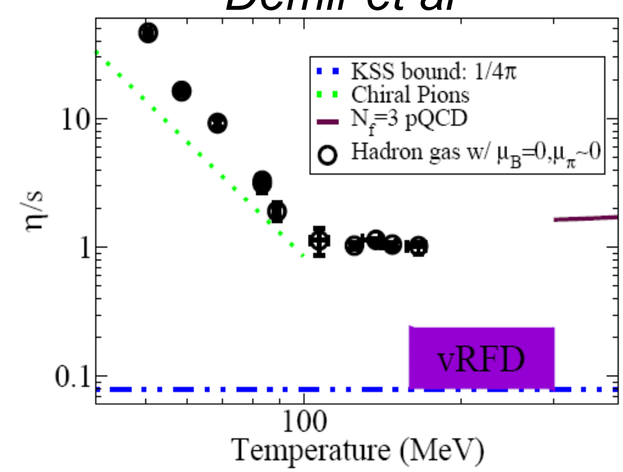
✓ *Strong coupling*

✓ *η/s - small*

Flow is partonic



Demir et al

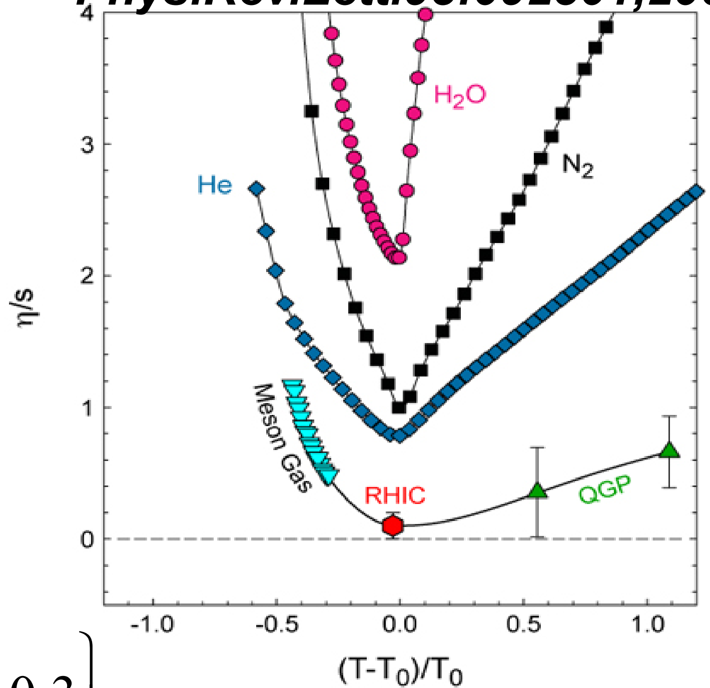


η/s from hadronic phase is very large 10-12x(1/4π) No room for such values!

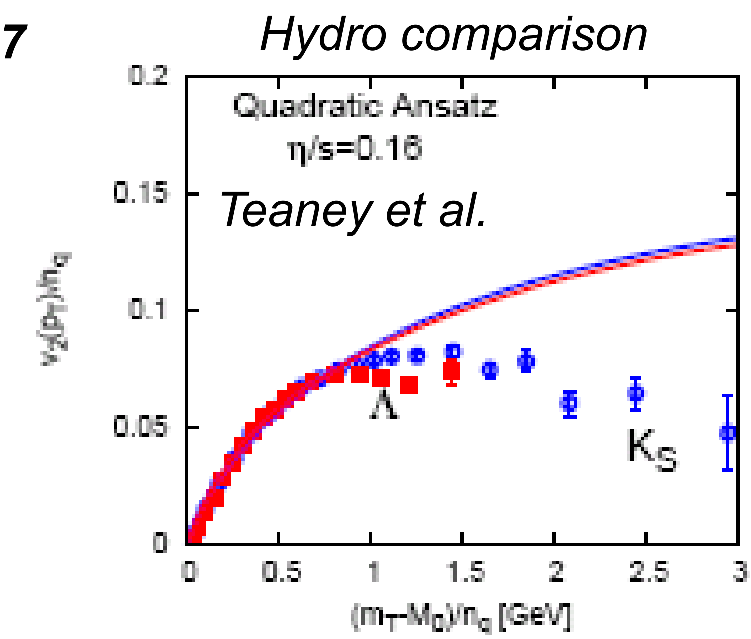
Partonic flow dominates!

The plasma is strongly coupled

Phys.Rev.Lett.98:092301,2007



Hydro comparison



$$4\pi\frac{\eta}{s} \sim 1.3 \pm 0.3$$

$$\lambda \sim 0.25 \text{ fm}$$

$$T_f \sim 165 \text{ MeV}$$

$$\langle T \rangle \sim 200 \text{ MeV}$$

Strong Coupling?

$$\hat{q} \sim 1 \frac{GeV^2}{fm}$$

For both light partons and heavy quarks

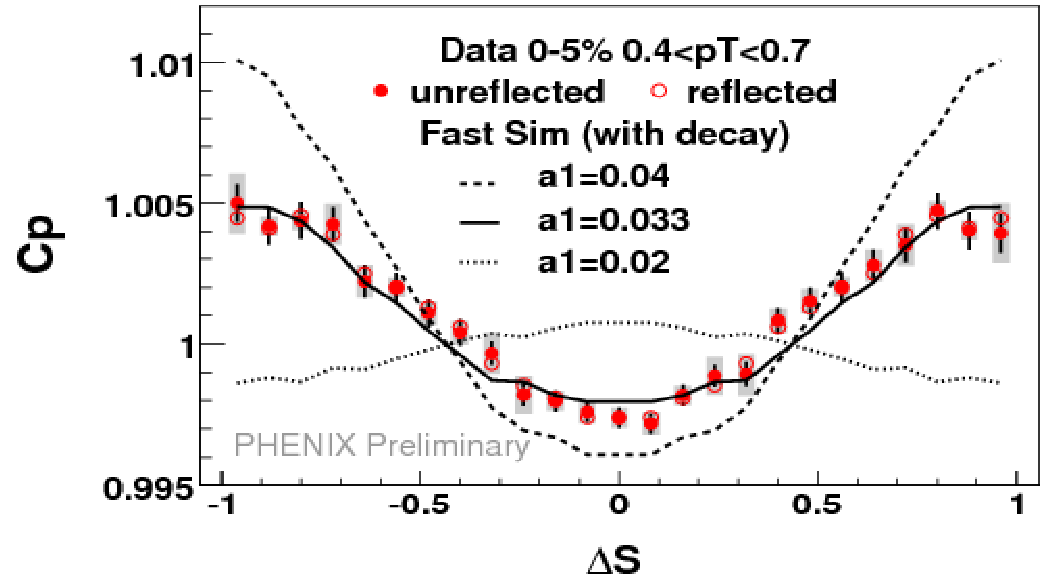
The fluid which leads to large collective flow is also responsible for strong jet quenching

Summary

• **PHENIX measurements of azimuthal charge-asymmetry presented for two separate methods**

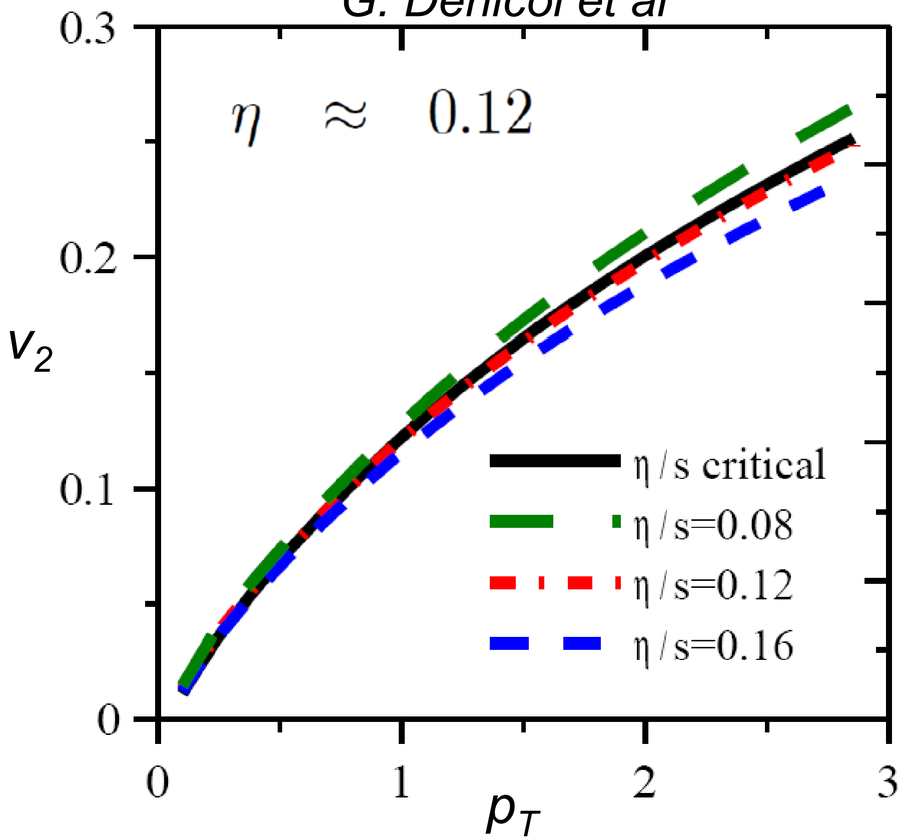
➢ **Azimuthal charge-asymmetry observed..**

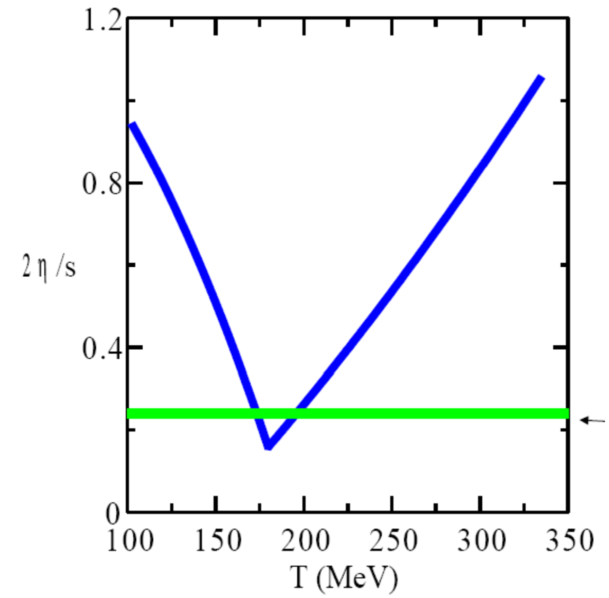
➢**PHENIX measurements are robust, pervasive and rife with opportunity for detailed model comparisons.**

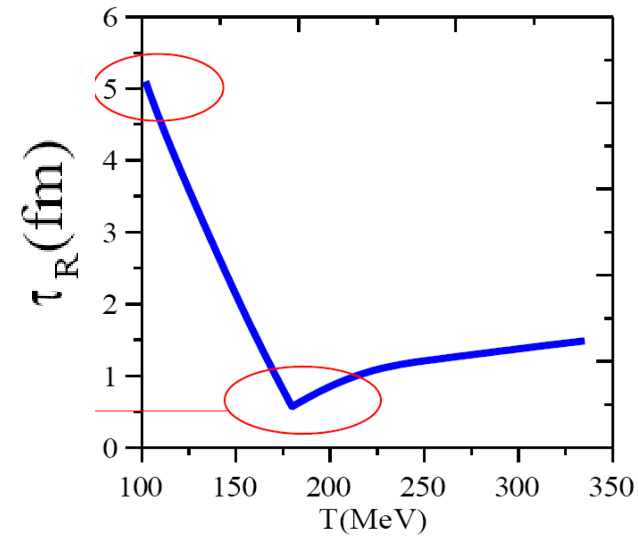


Estimates for η/s

G. Denicol et al







Relaxation time limits η/s to small values