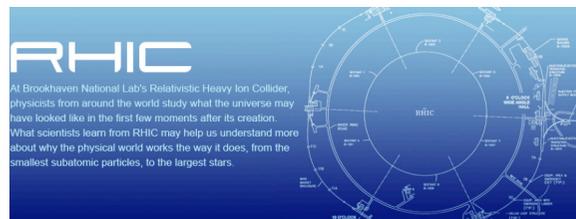
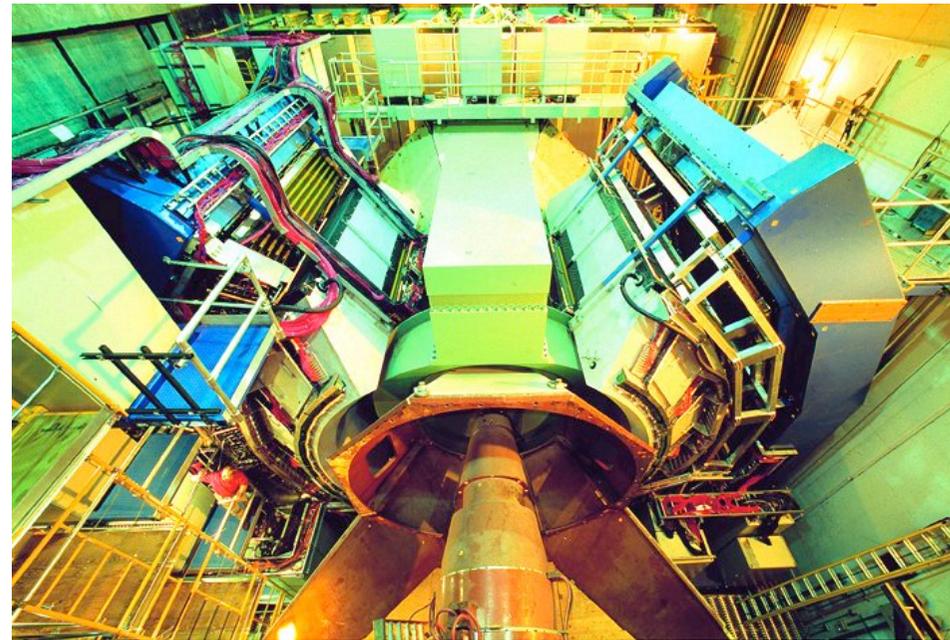


Collective Flow Measurements from the PHENIX Experiment

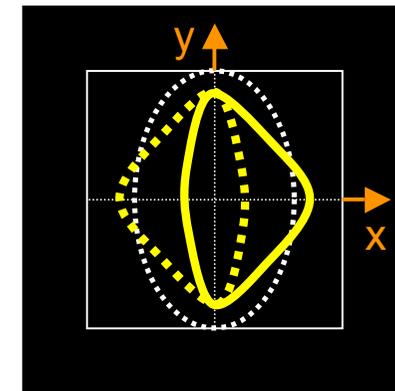
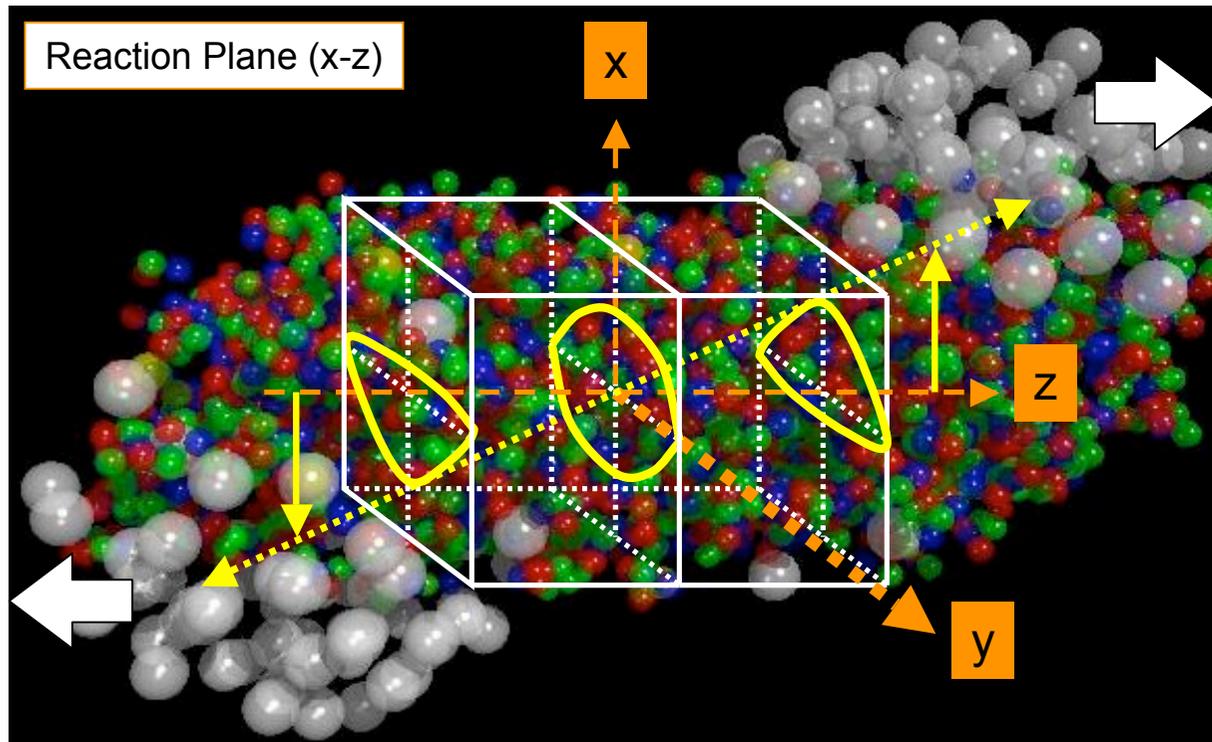
Shinichi Esumi for the PHENIX Collaboration

CONTENTS

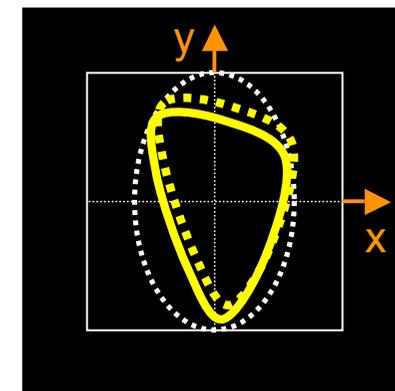
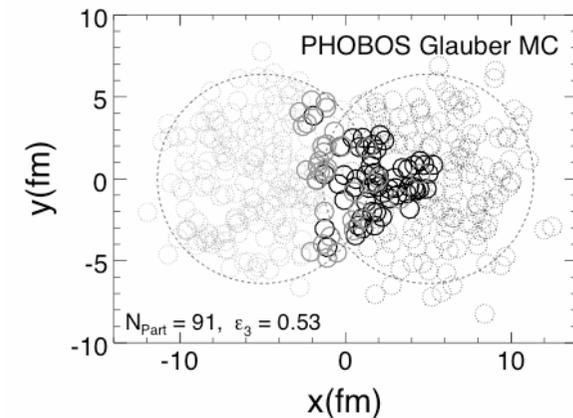
higher order event anisotropy
event plane correlation
 v_2, v_3, v_4 in 200GeV Au+Au
2-particle correlation
energy dependence of v_n
direct-photon v_2



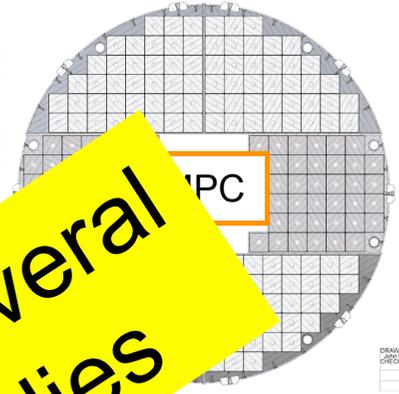
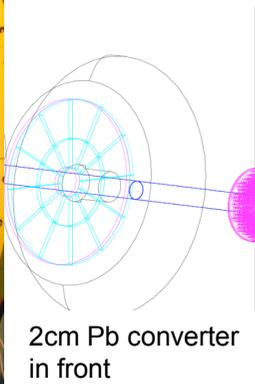
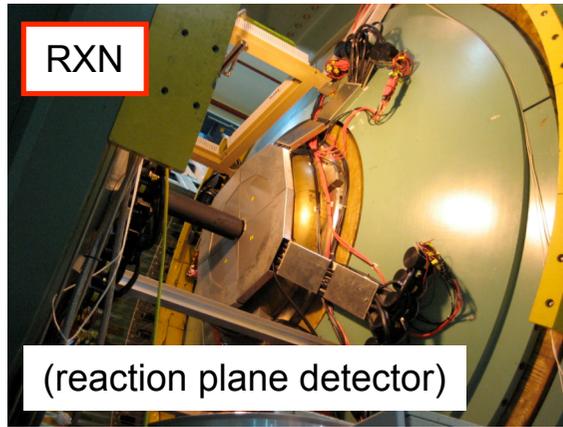
v_3 and Initial Fluctuation



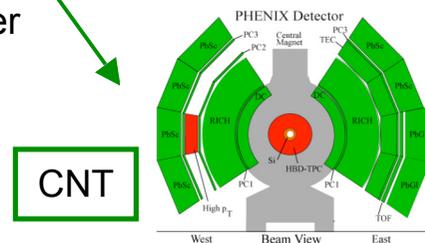
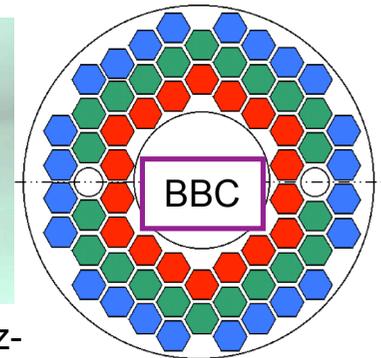
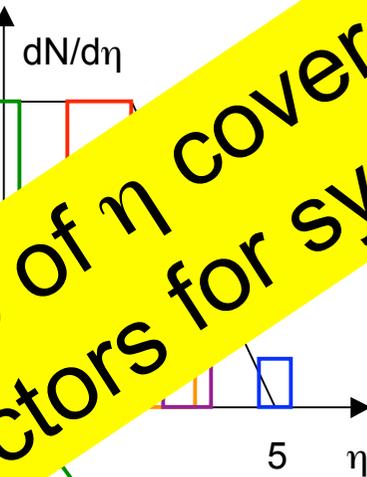
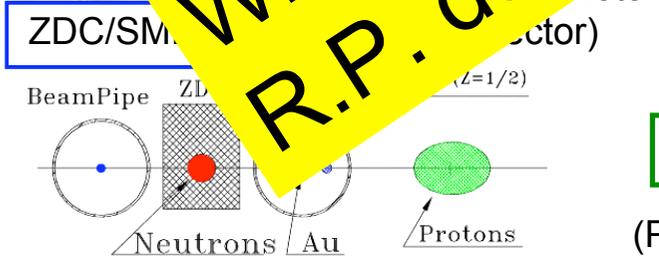
arXiv:1003.0194



black-disk --> sign-flipping v_3
 initial fluctuation --> no-sign-flipping v_3



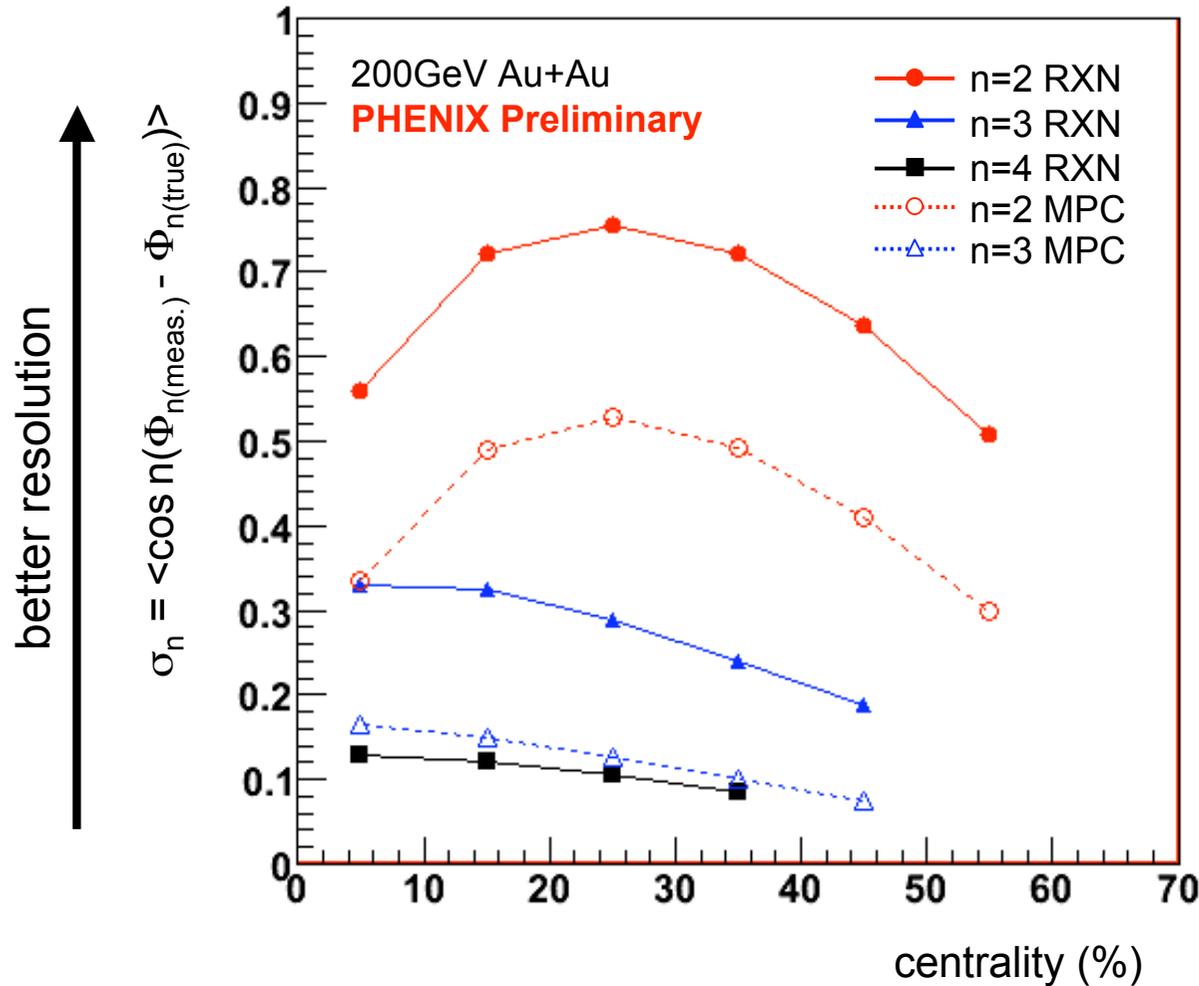
Wide range of η coverage with several R.P. detectors for systematic studies



CNT
(PHENIX central tracking arm)



Reaction plane resolution of n^{th} order plane

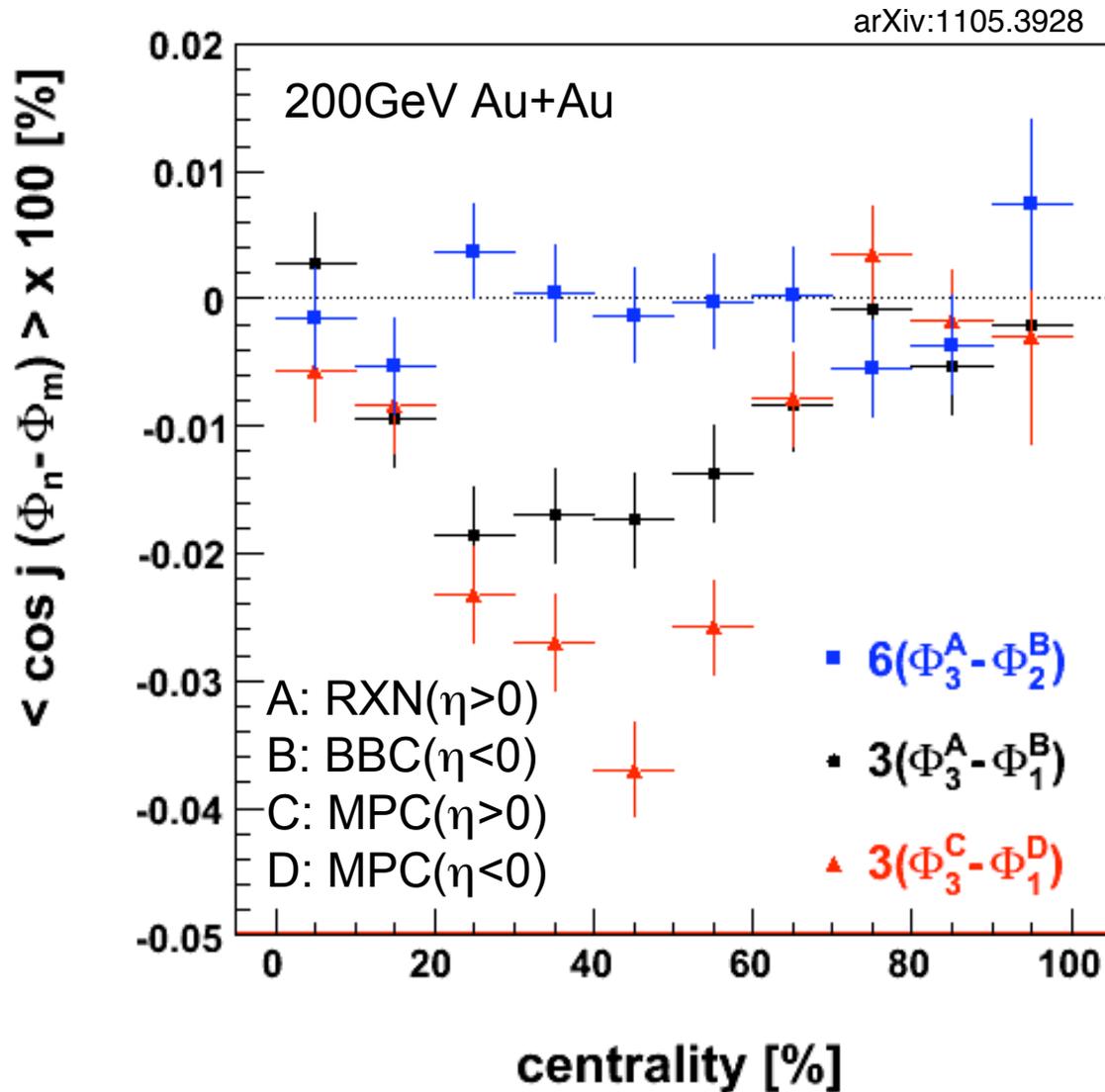


RXN $|\eta| = 1.0 \sim 2.8$
 MPC $|\eta| = 3.1 \sim 3.7$

positive correlation
 in Φ_3 between
 opposite η up to
 $\pm 3 \sim 4$

No sign flipping in Φ_3 observed
 --> Initial geometrical fluctuation

No visible correlation between Φ_3 and Φ_2



- same harmonics
 $2(\Phi_2 - \Phi_2) \sim 10\%$
 $3(\Phi_3 - \Phi_3) \sim 1\%$

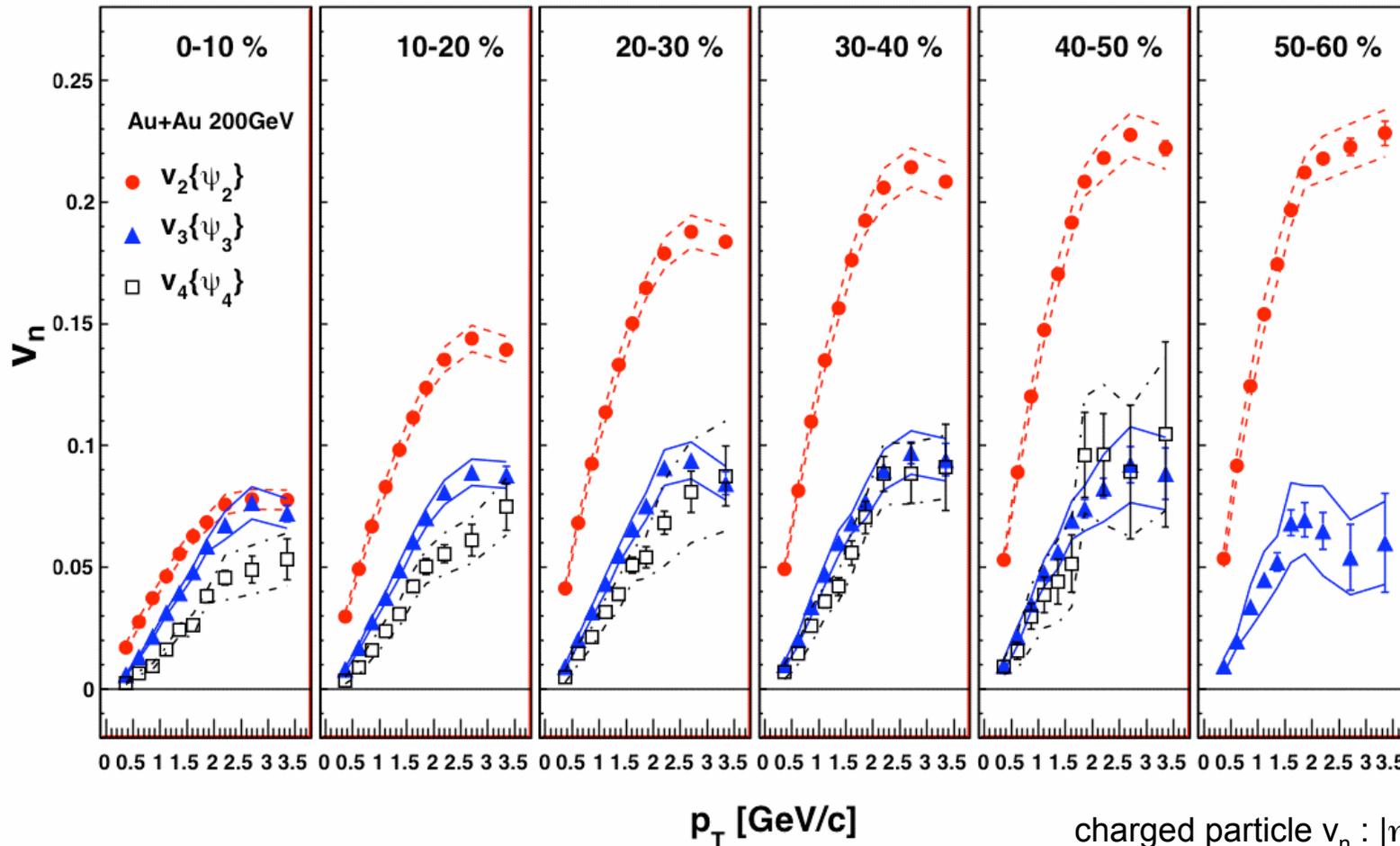
- weak negative correlation between Φ_3 and Φ_1

- hint for rapidity anti-symmetric v_3 contribution

Fluctuation dominance for Φ_3

$v_2\{\Phi_2\}$, $v_3\{\Phi_3\}$, $v_4\{\Phi_4\}$ at 200GeV Au+Au

arXiv:1105.3928



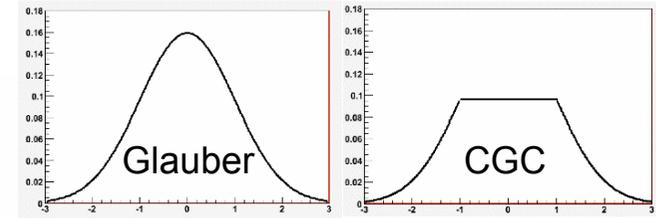
charged particle v_n : $|\eta| < 0.35$
 reaction plane Φ_n : $|\eta| = 1.0 \sim 2.8$

- (1) v_3 is comparable to v_2 at 0~10%
- (2) weak centrality dependence on v_3
- (3) $v_4\{\Phi_4\} \sim 2 \times v_4\{\Phi_2\}$

All of these are consistent with initial fluctuation.

v_3 breaks the degeneracy

arXiv:1105.3928



Smaller
eccentricity

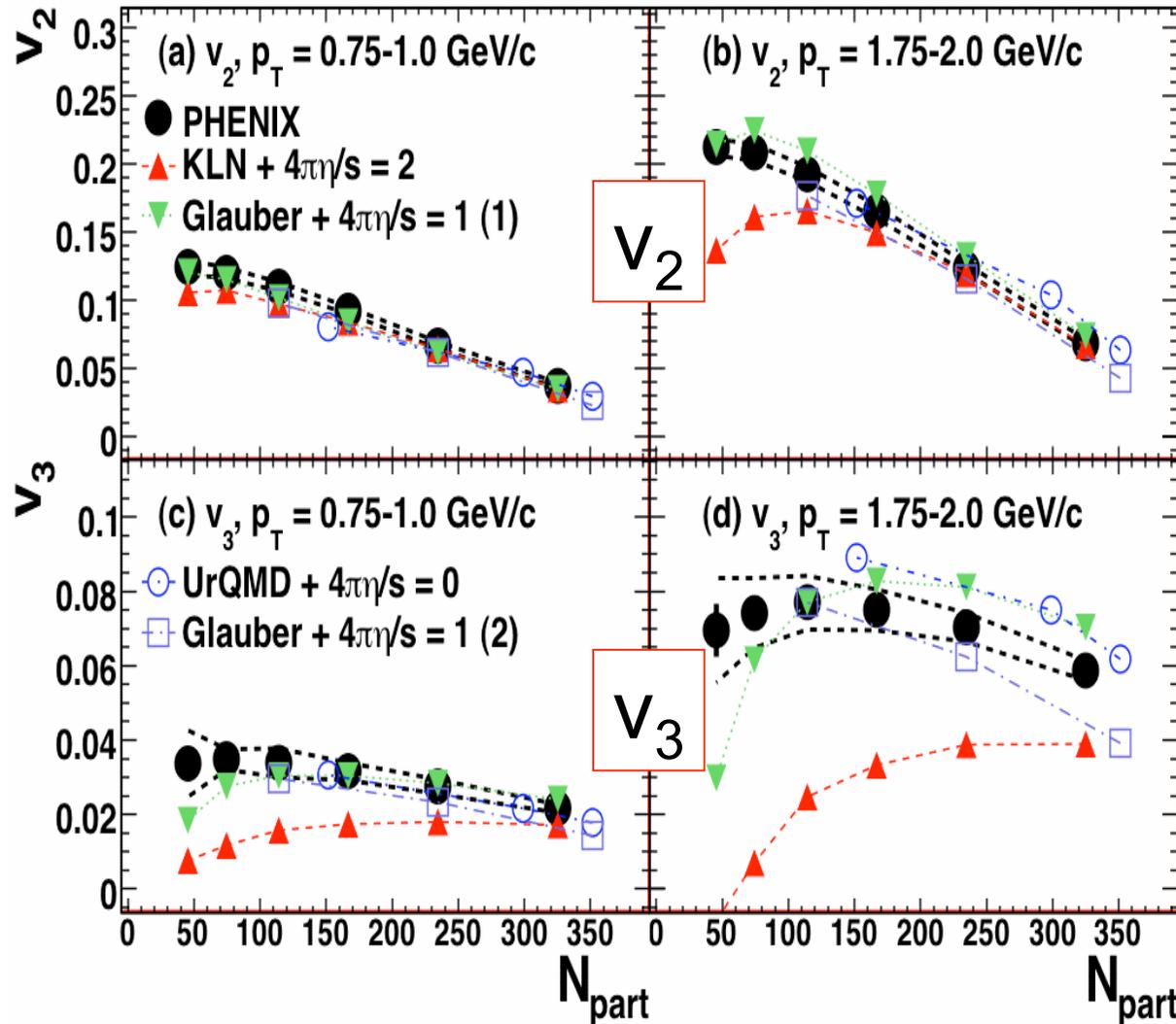
Larger
eccentricity

v_3 provides an additional
constraining power on
the hydro-model.

Glauber & $4\pi\eta/s=1$
works

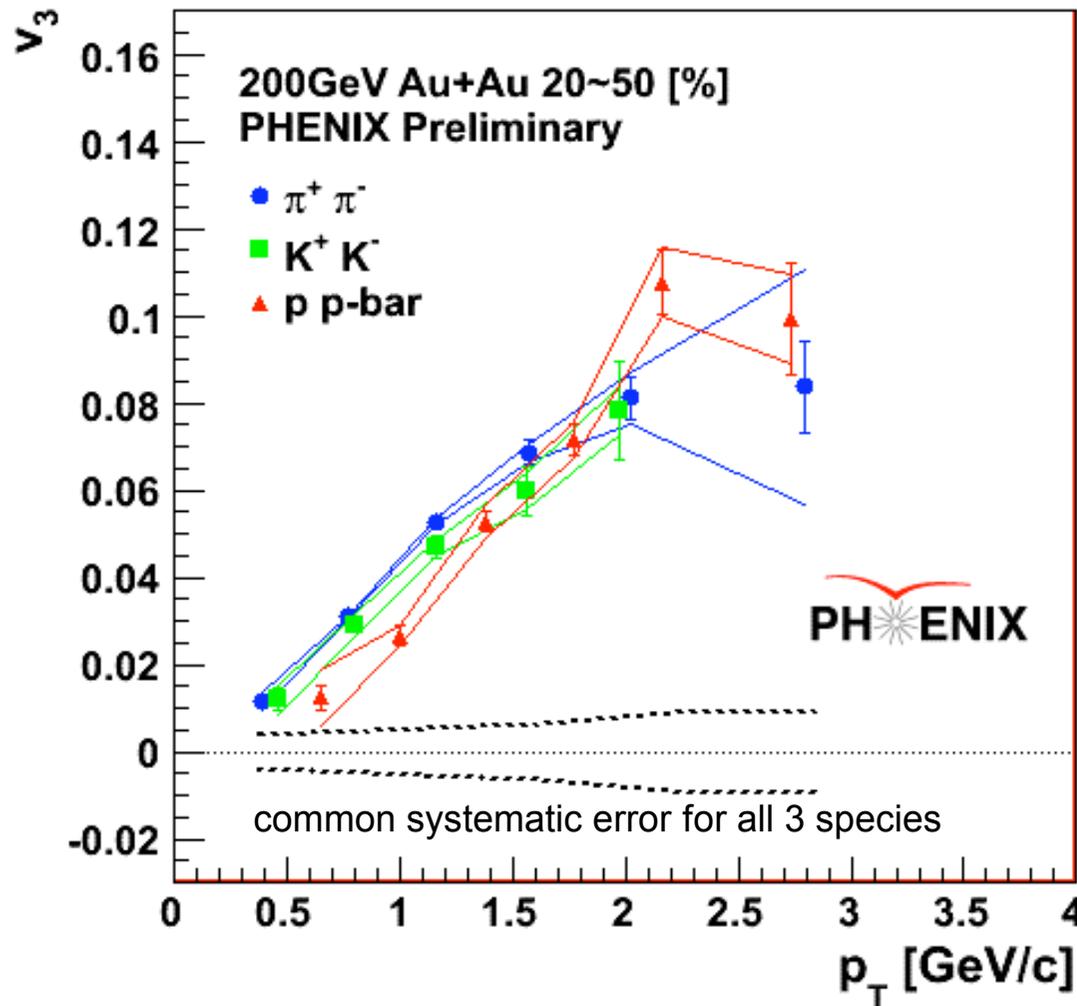
CGC-KLN & $4\pi\eta/s=2$
fails

B. Alver et. al., Phys. Rev. C82, 034913(2010).
B. Schenke et. al., Phys. Rev. Lett. 106, 042301(2011).
H. Petersen et. al., Phys. Rev. C82, 041901(2010).



Glauber & $4\pi\eta/s=1$ favored

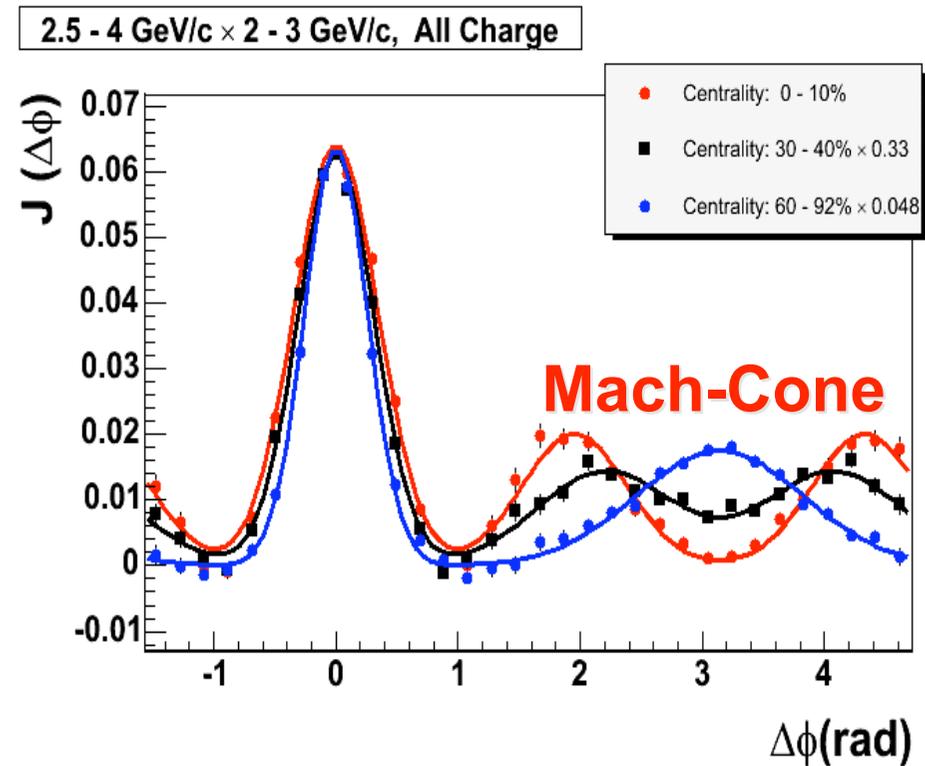
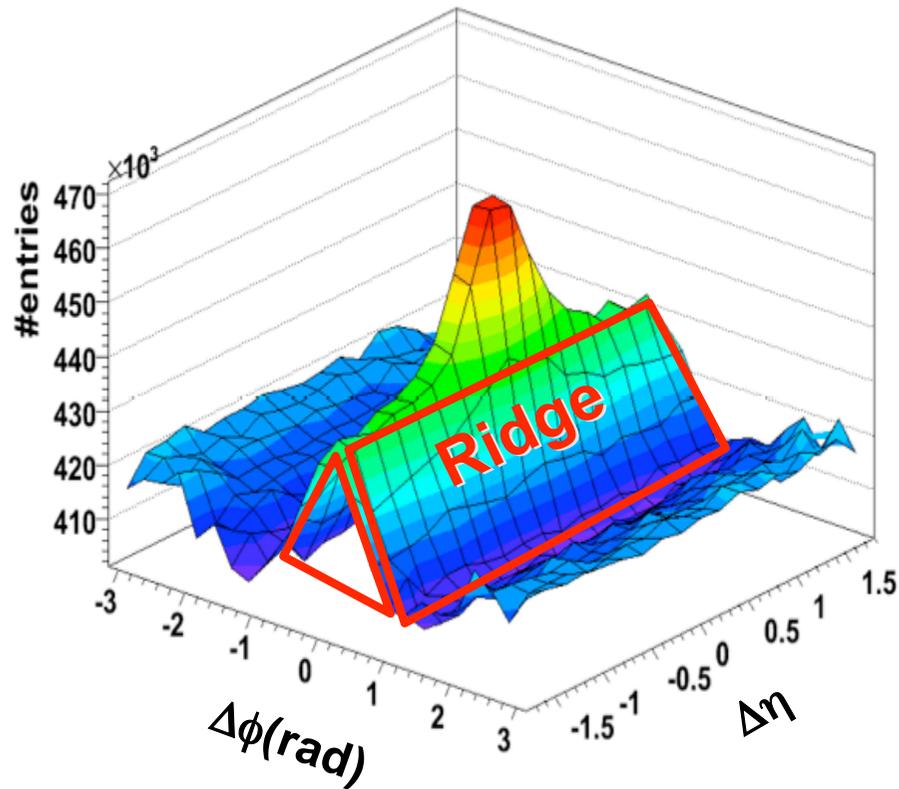
Identified $\pi/K/p$ $v_3\{\Phi_3\}$ at 200GeV Au+Au



- lower p_T
particle mass
dependence
radial flow
- intermediate p_T
baryon / meson
splitting
quark coalescence
at hadronization with
partonic v_3

Radial & Partonic collective flow seen in v_3

Does v_3 explain Ridge and Mach-Cone?

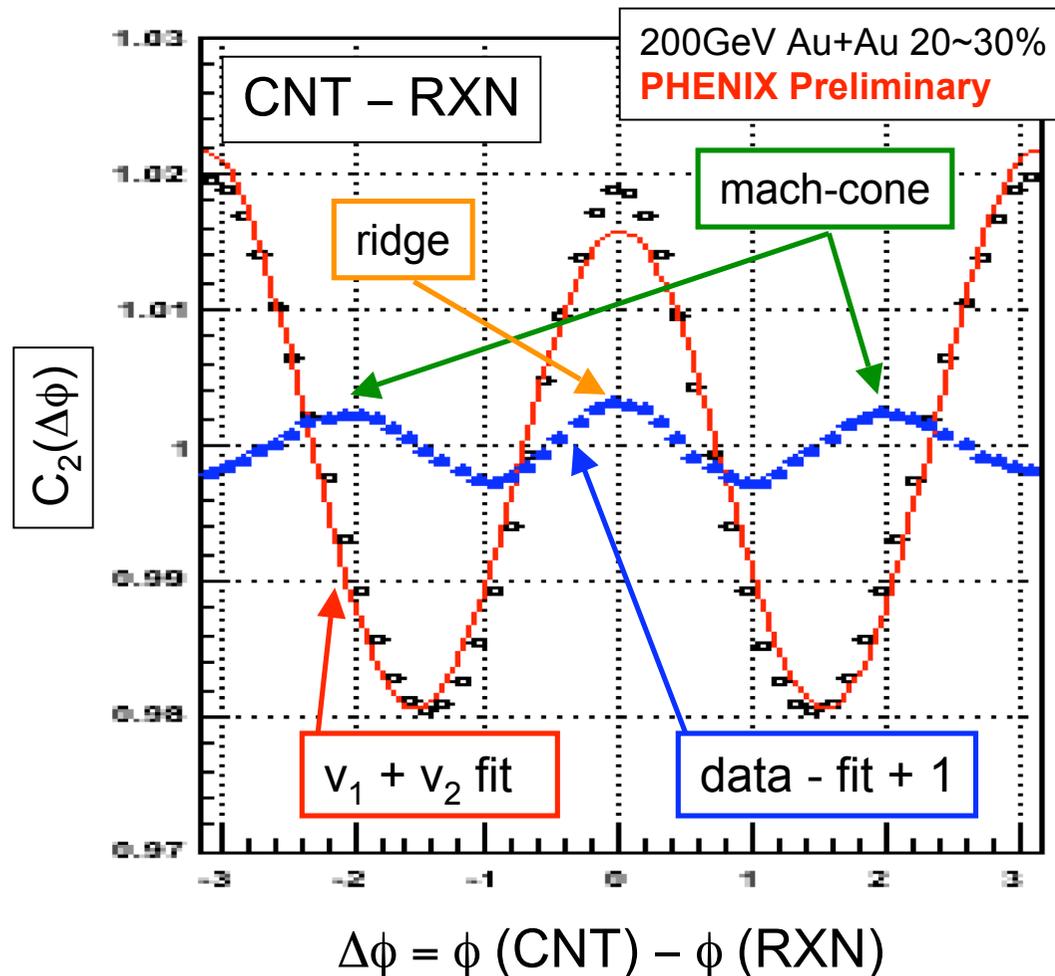


Ridge : long range $\Delta\eta$ correlation at near-side

Cone : double peak/shoulder at away-side (long in $\Delta\eta$)

v_3 : initial fluctuation is common over wide range of η

2-particle correlation between central and forward

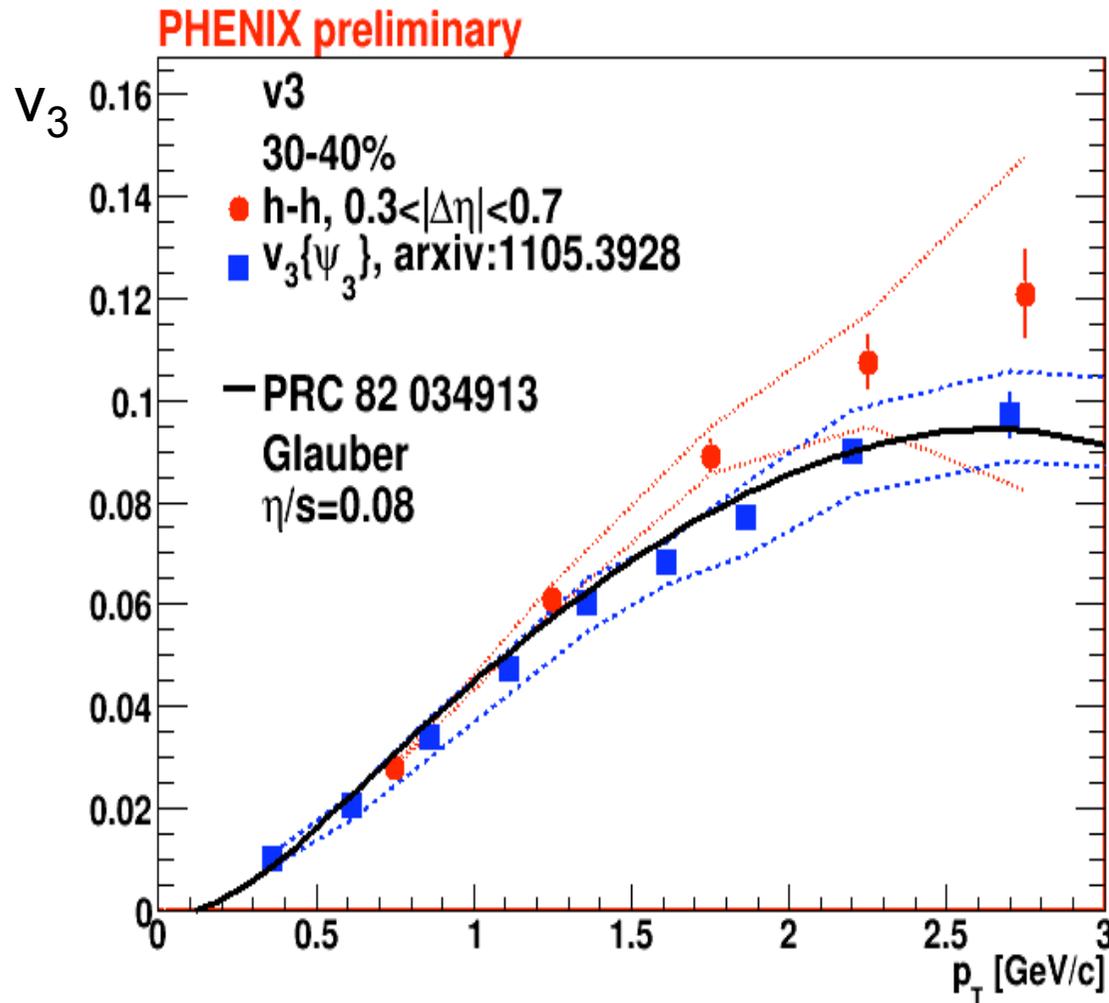


RXN: $|\eta|=1.0\sim 2.8$
 CNT: ($|\eta|<0.35$)
 charged hadrons
 $p_T=2\sim 4(\text{GeV}/c)$

clear 3rd order moment
 seen in long range $\Delta\phi$
 correlation

another way of
 extracting the v_n
 parameters with
 forward anisotropy v_n
 without using Φ_n

2-particle correlation between central and central



Bulk flow + jet
(cent.-cent. 2-part.)

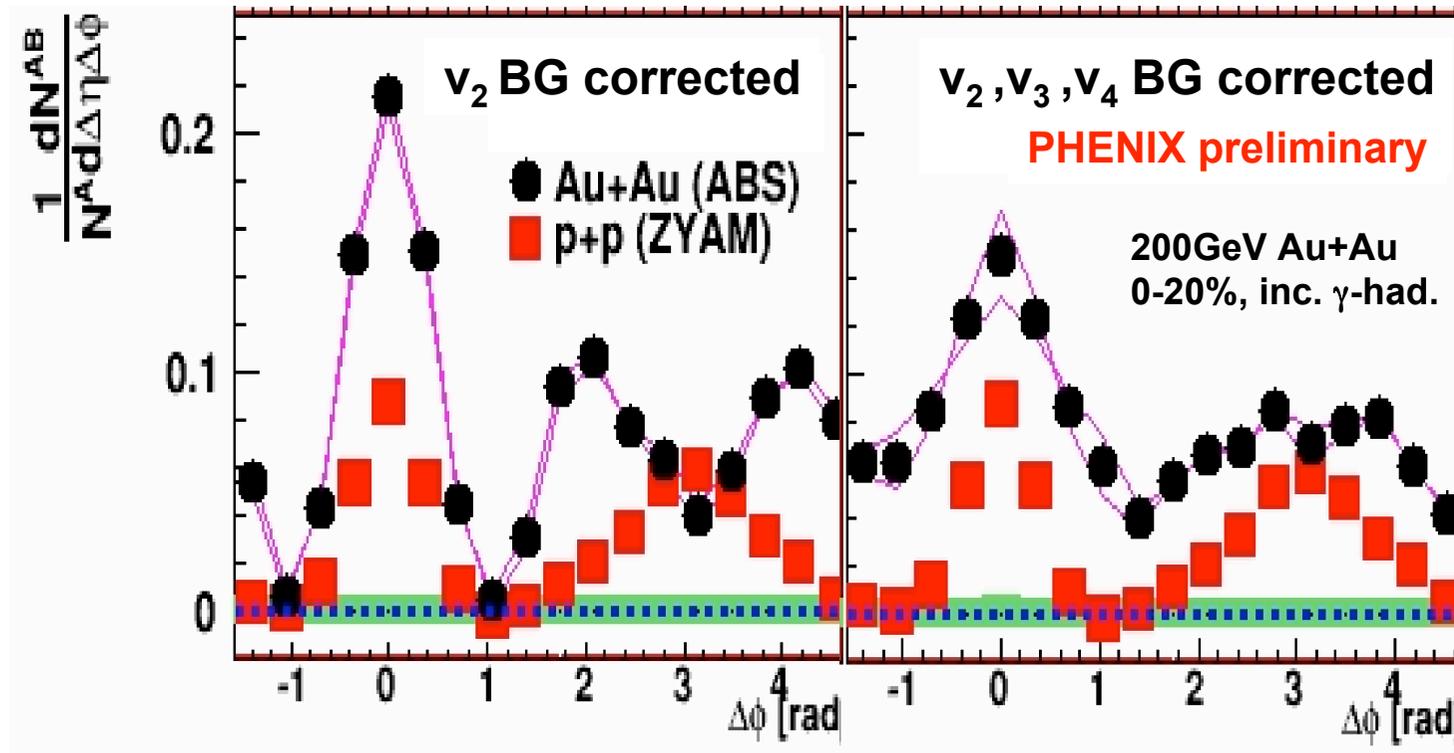
↕ small difference

Bulk flow
(forw. Φ_3 E.P.)

Hydro model with
Glauber & $4\pi\eta/s=1$
works

B. Alver et. al., Phys. Rev. C82, 034913(2010).

Flow subtraction/correction with measured v_n for central-central 2-particle correlation



mach-cone is mostly gone
 remaining medium effect seen
 (correlated pair yield by absolute normalization)

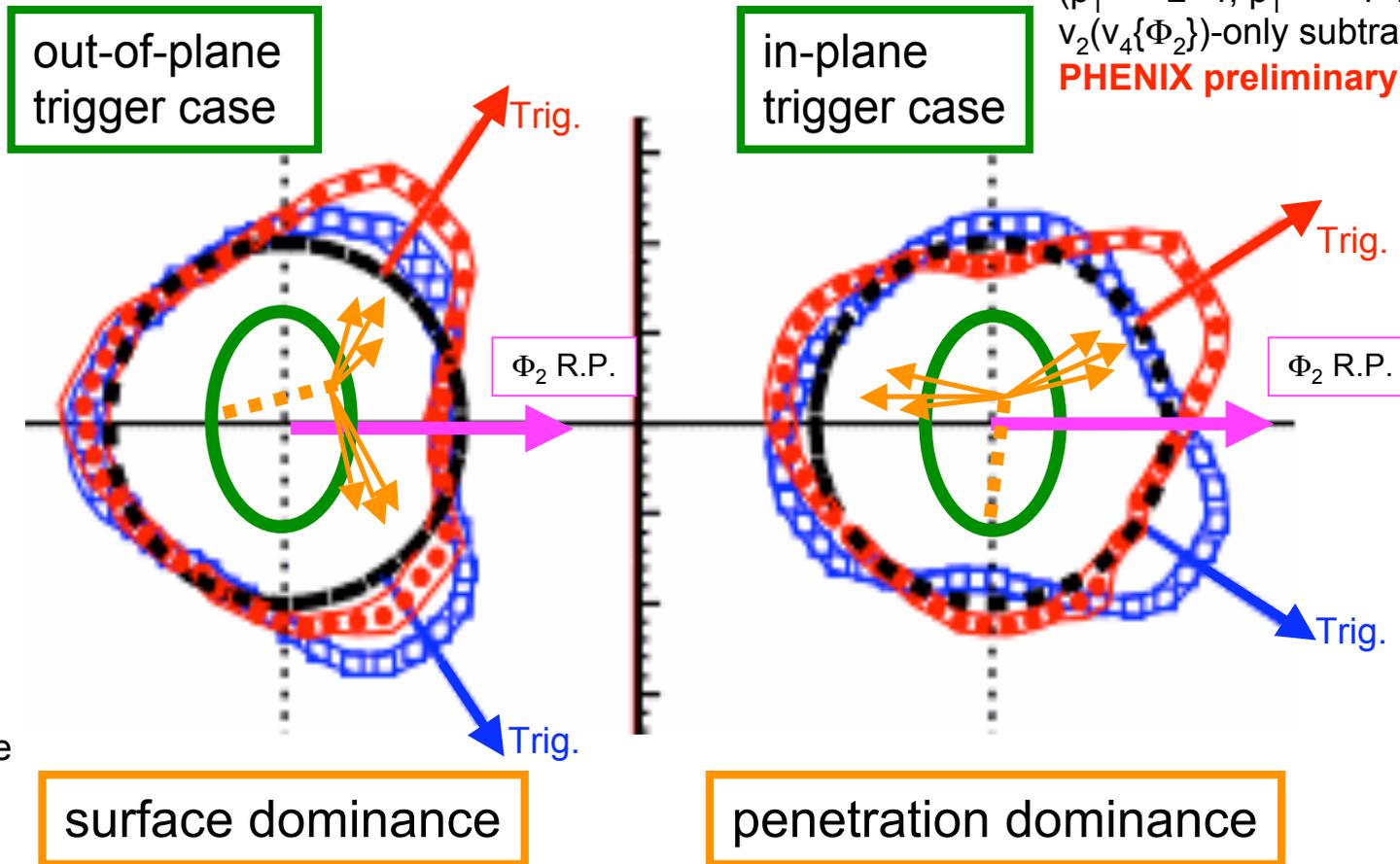
Observed left/right asymmetry remains after “the usual/normal” v_3 subtraction.

200GeV Au+Au \rightarrow h-h
 $(p_T^{\text{Trig}}=2\sim 4, p_T^{\text{Asso}}=1\sim 2\text{GeV}/c)$
 $v_2(v_4\{\Phi_2\})$ -only subtraction
PHENIX preliminary

Trigger angle selection w.r.t. Φ_2 separately for **left(up)** / **right(down)**

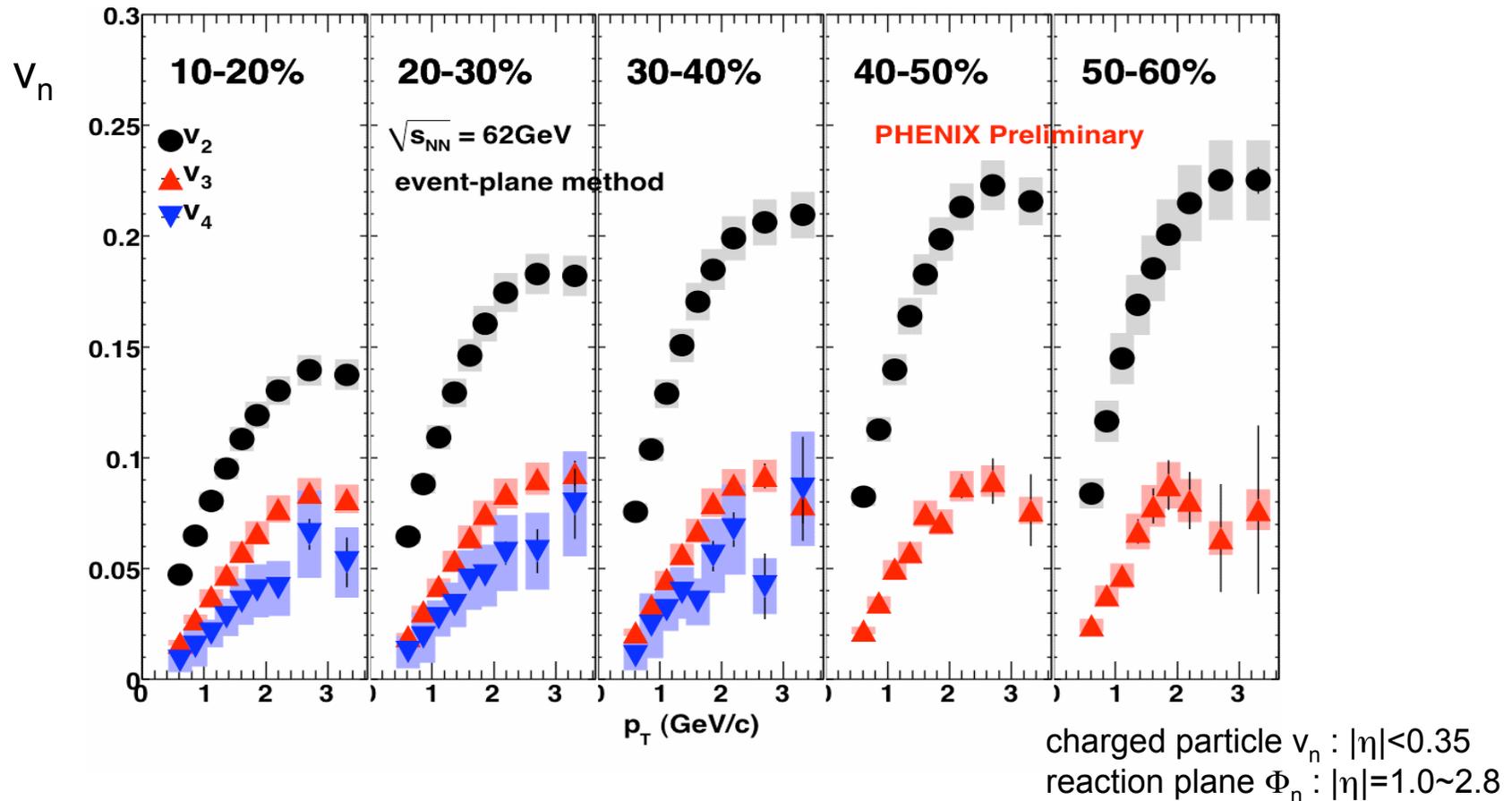
Trigger angle selected 2-part. corr. data are plotted in polar coordinate by rotating Φ_2 R.P. angle as X-axis.

Flow subtracted yield is shown radially with base line. ■■■■■■



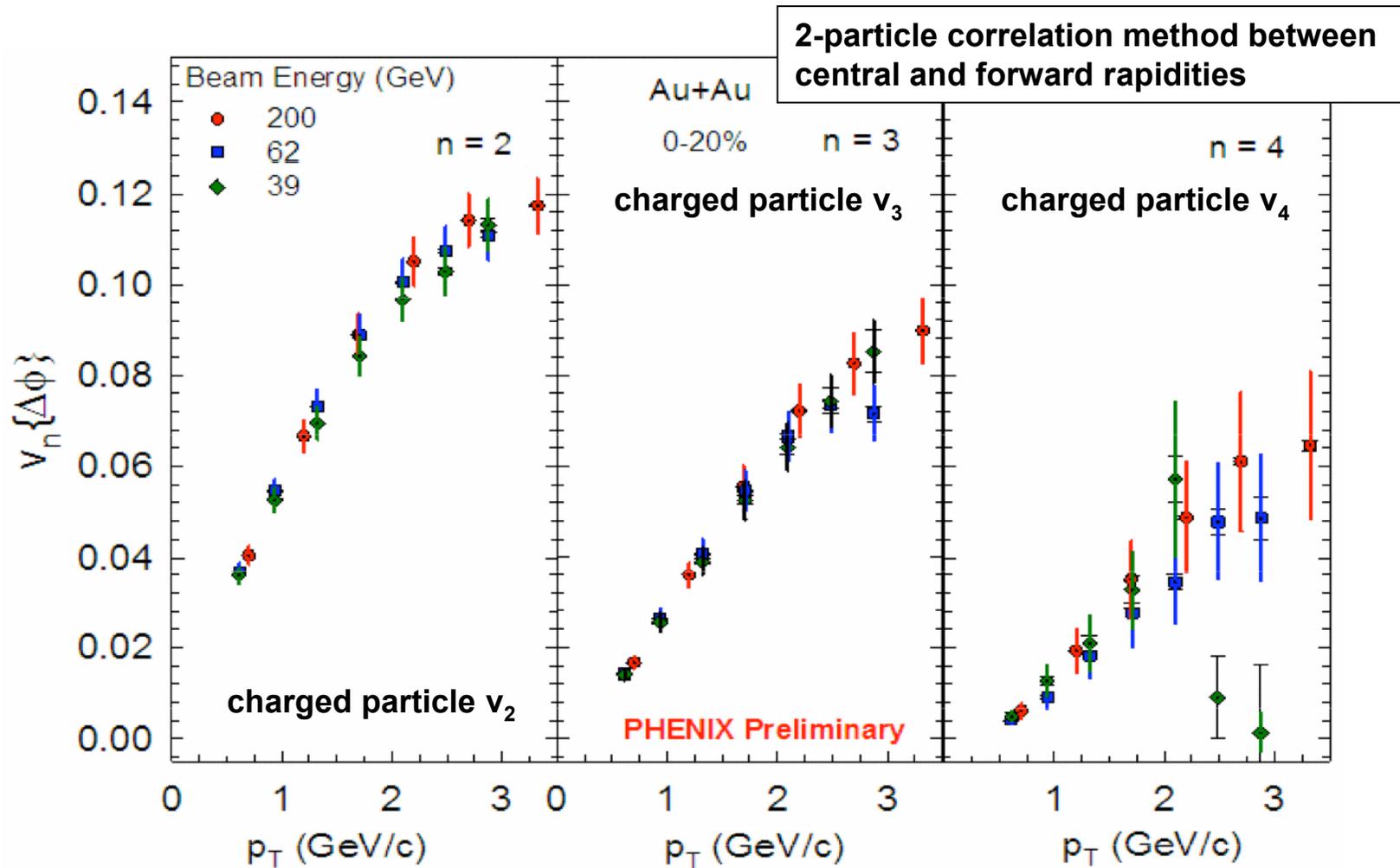
Two competing processes seen

$v_2\{\Phi_2\}$, $v_3\{\Phi_3\}$, $v_4\{\Phi_4\}$ at 62GeV Au+Au



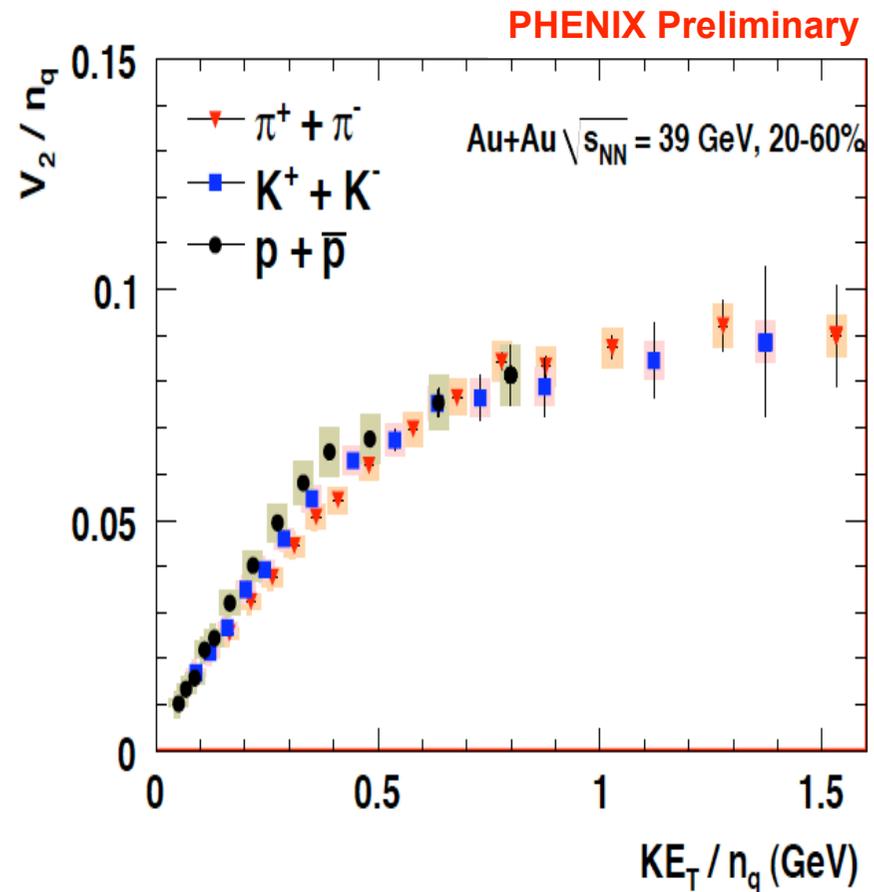
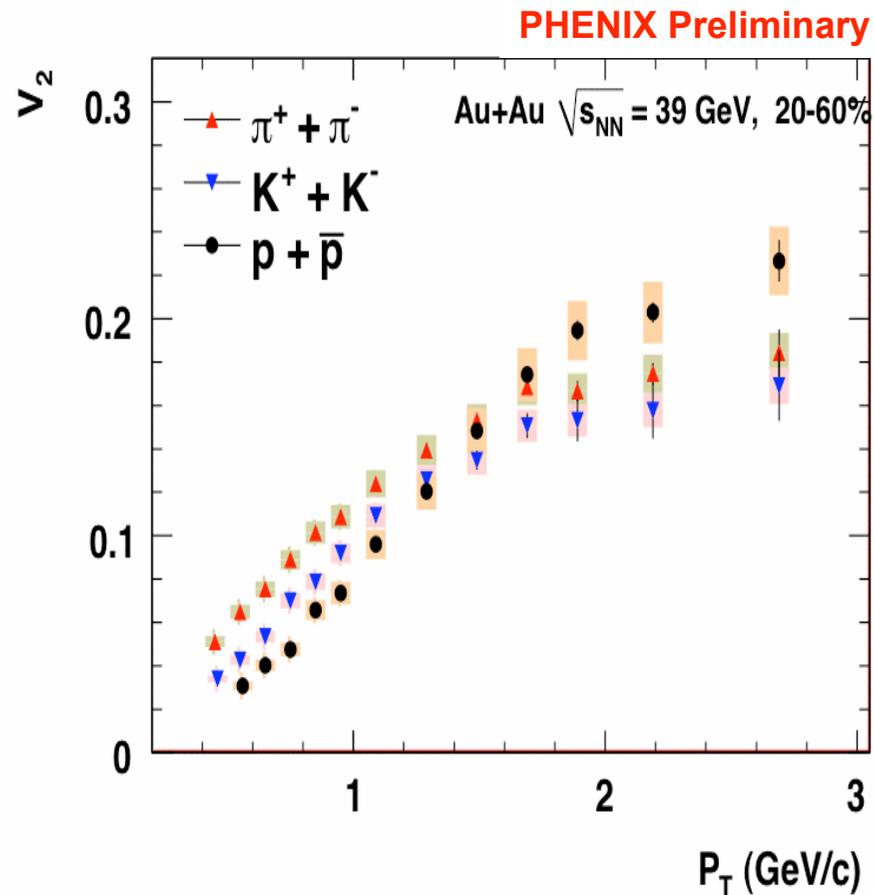
similar results down to Au+Au 39GeV

Beam energy dependence 39/62/200GeV Au+Au



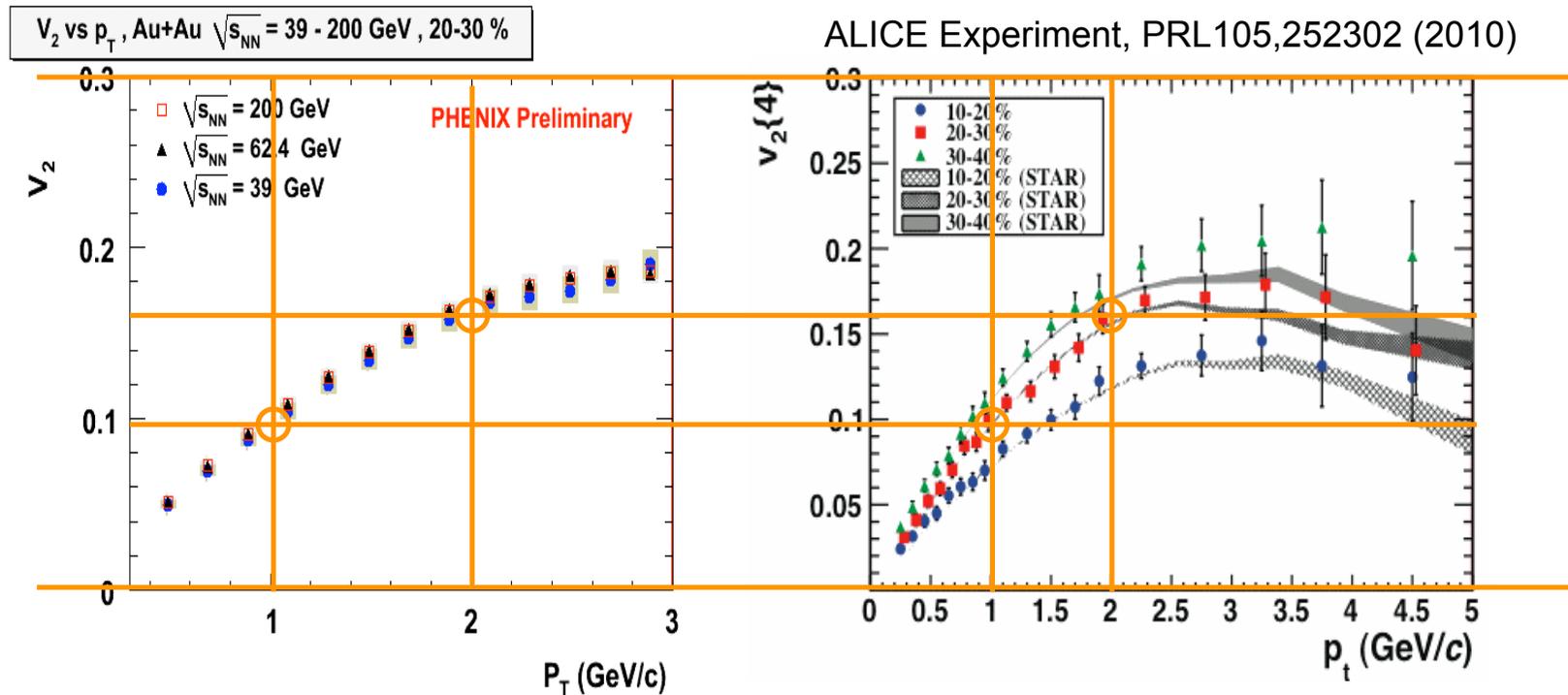
similar hydro-properties down to 39GeV

Identified hadron v_2 at 39GeV Au+Au (similar for 62GeV Au+Au)



Partonic collective flow down to 39GeV

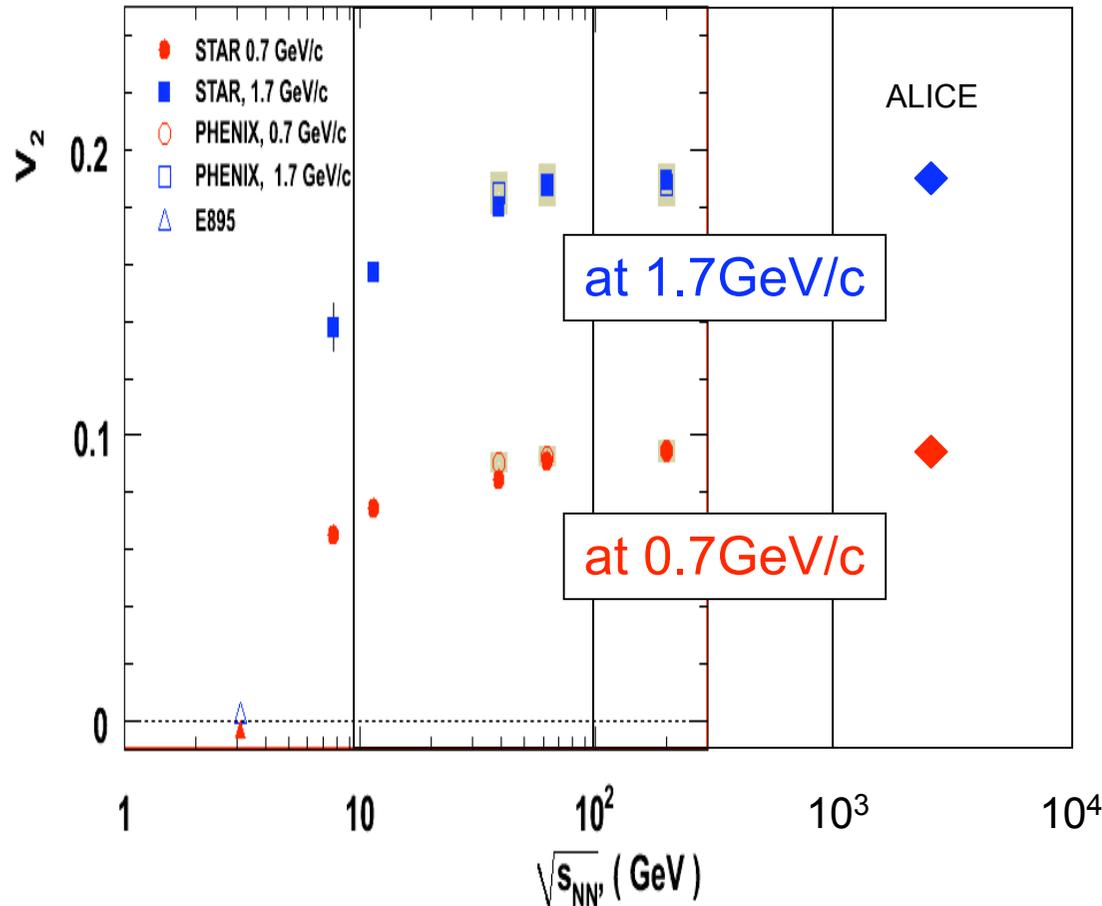
Comparable v_2 vs p_T from 39GeV to 2.76TeV



similar hydro-properties from 39GeV to 2.76TeV

Saturation of v_2 with beam energy

Preliminary, STAR, PHENIX and E895 data



saturation of v_2 for given p_T around or below 39 GeV

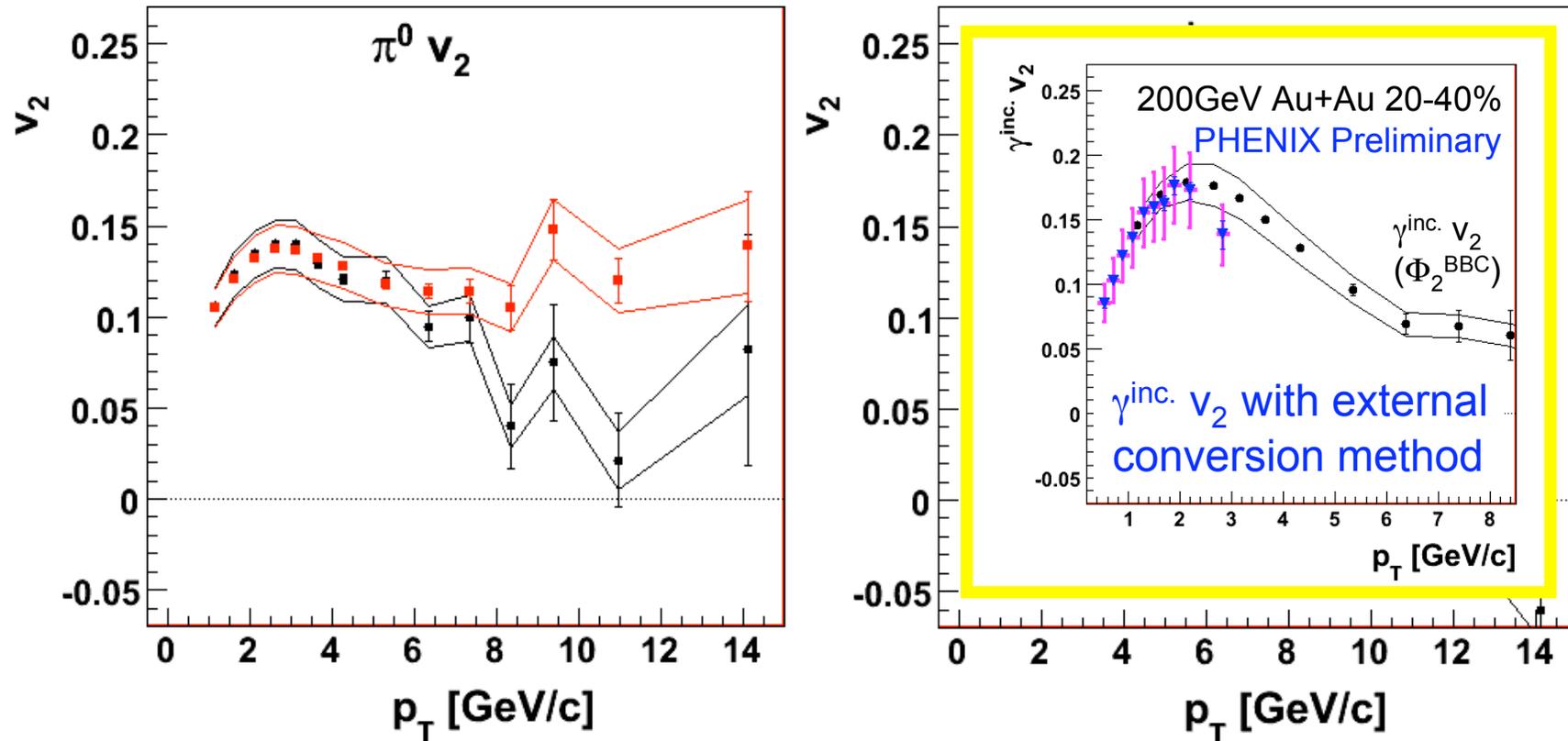
$\langle v_2 \rangle$ still increases mainly because of the $\langle p_T \rangle$ rise.

Almost perfect fluidity from 39 GeV to 2.76 TeV

Measurement of π^0 and $\gamma^{\text{inc.}}$ v_2

200GeV Au+Au (min. bias)

arXiv:1105.4126

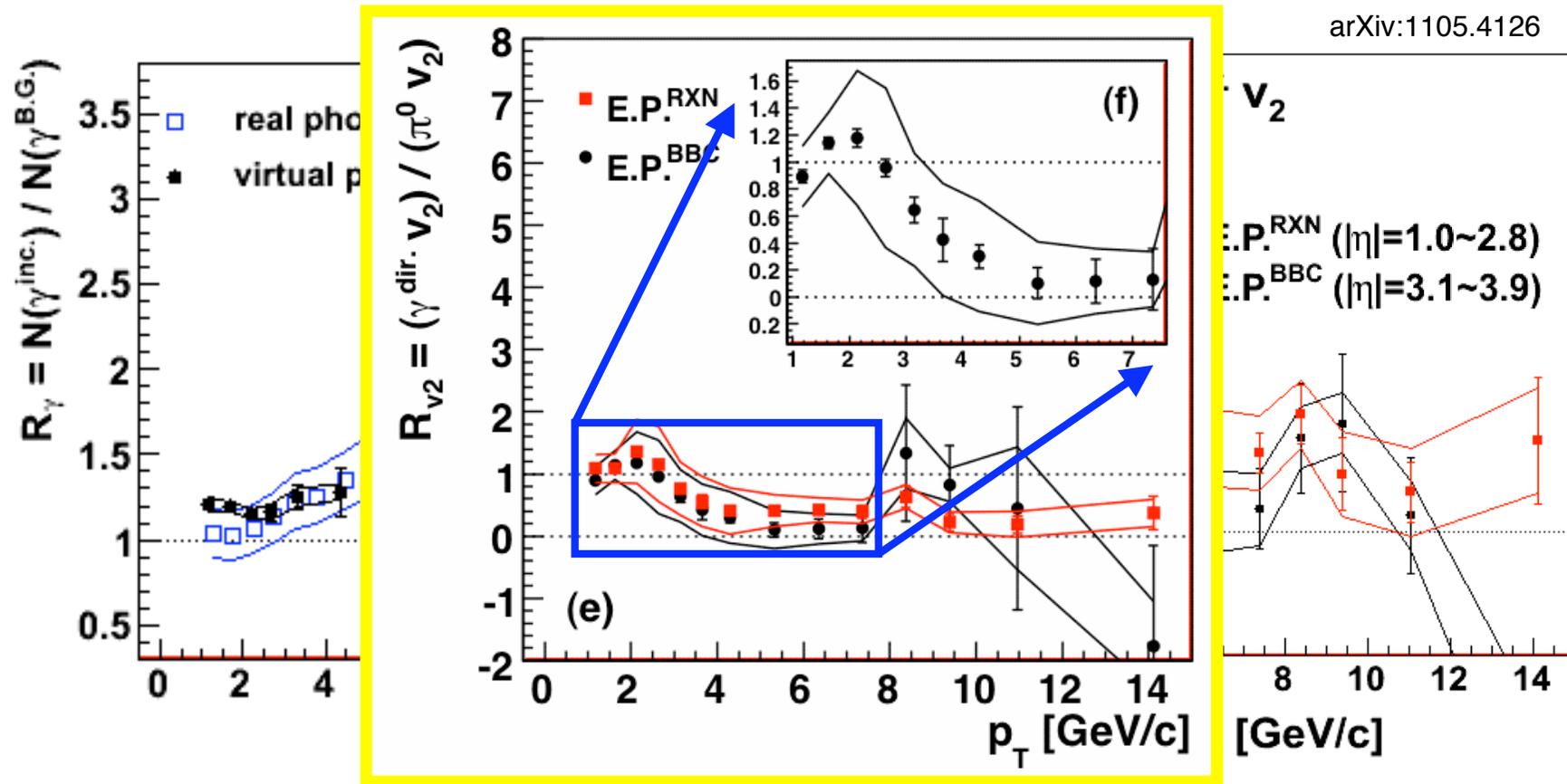


significant difference between π^0 and $\gamma^{\text{inc.}}$ v_2 above 5 GeV/c,
difference between $v_2^{\{\text{RXN}\}}$ and $v_2^{\{\text{BBC}\}}$ due to jet bias.

R_γ ratio and extracted $\gamma^{\text{dir.}} v_2$

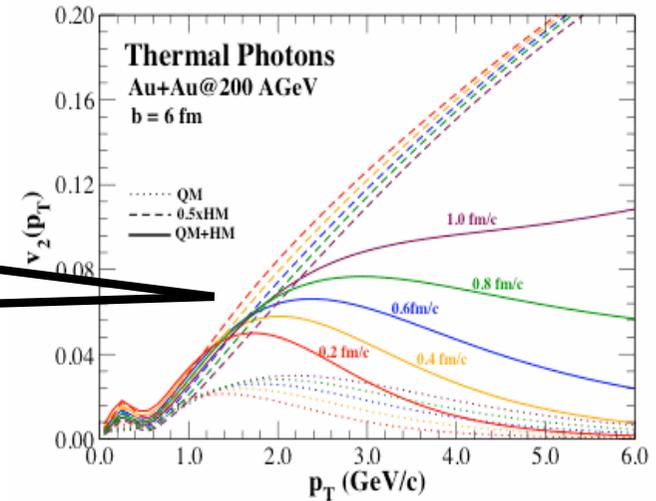
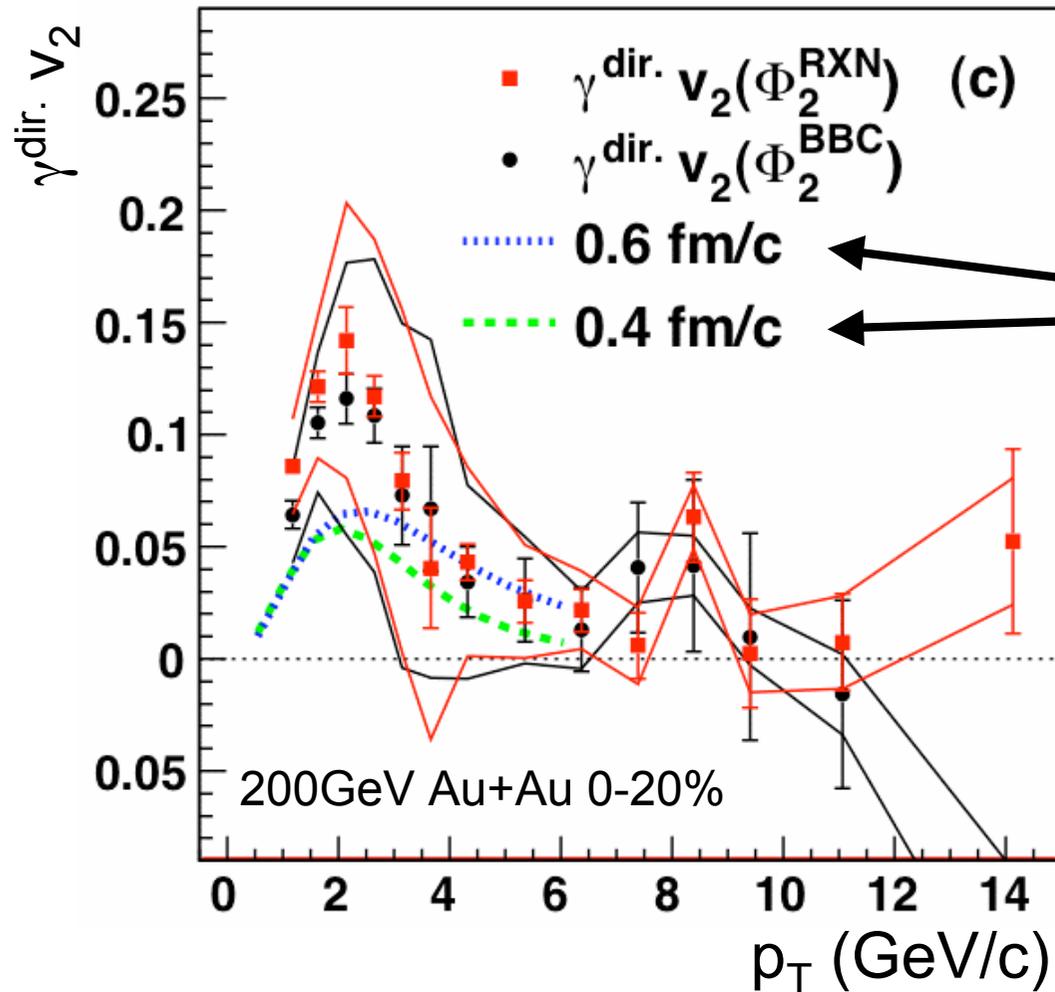
200GeV Au+Au (min. bias)

arXiv:1105.4126



$\gamma^{\text{dir.}} v_2$ is small at high p_T --> consistent with prompt photon
surprisingly large $\gamma^{\text{dir.}} v_2$ seen, similar to hadron v_2 at low p_T .

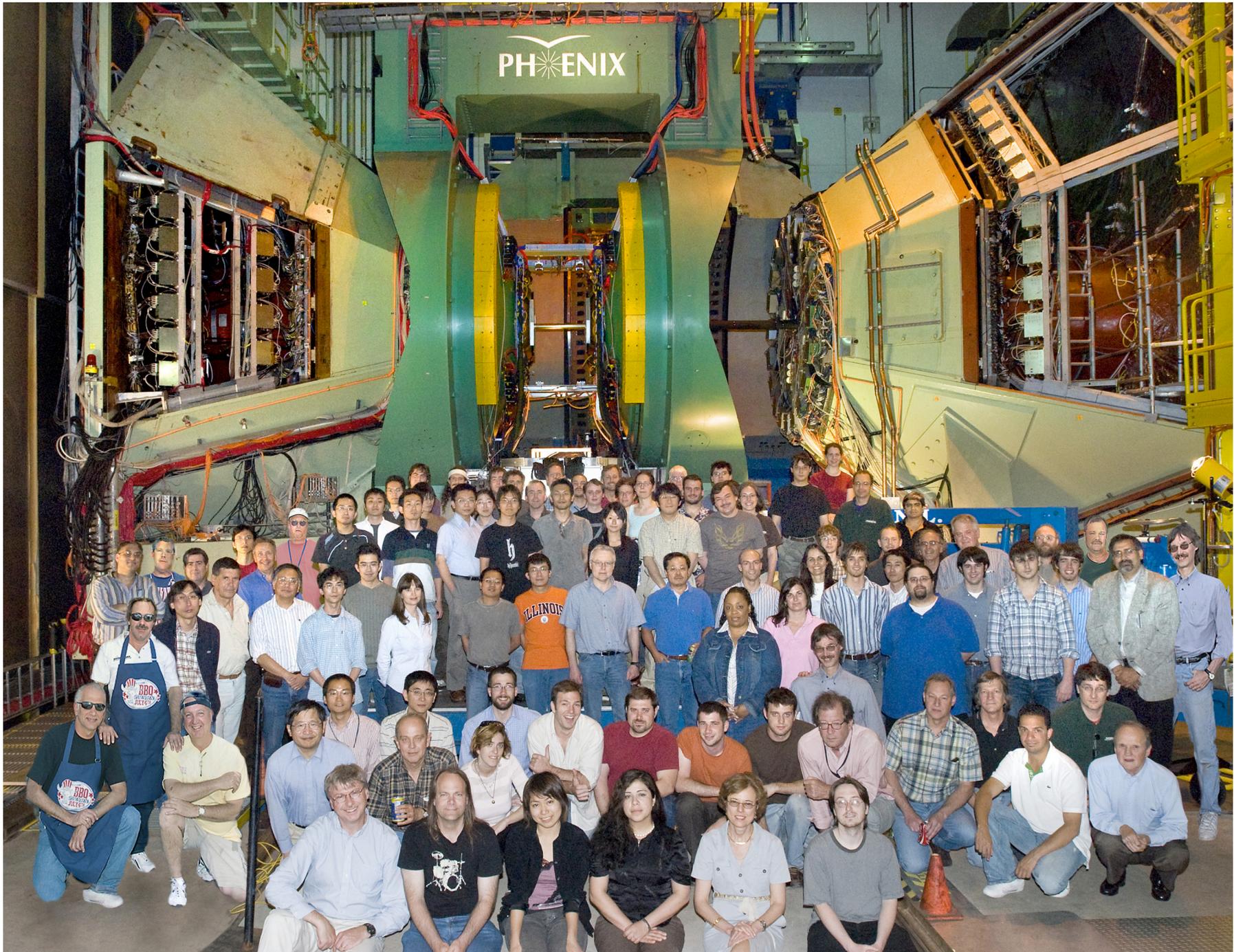
Comparison of $\gamma^{\text{dir.}} v_2$ with model calculations



R. Chatterjee and D. K. Srivastava
 PRC 79, 021901(R) (2009)
 PRL96, 202302 (2006)

Several models have failed in v_2 magnitude with similar shape

Large v_2 of low p_T thermal photon
 --> challenge to theory calculations



PHENIX Flow talk at Quark Matter 2011, May 24, Anncy, France

ShinIchi Esumi, Univ. of Tsukuba

Related PHENIX talks

“PHENIX Measurements of Higher-order Flow Harmonics in Au+Au Collisions at $\sqrt{s_{NN}}=200$ GeV: Implications for Initial-eccentricity Models and the Specific Viscosity of the Quark Gluon Plasma”

[Mon.23-May-2011 18:30-18:50 Parallel 1-7 Global and collective dynamics]

Roy Lacey (Stony Brook Phys.)

“Measurement of Light Vector Mesons by PHENIX Experiment at RHIC”

[Mon.23-May-2011 18:50 Parallel 1-8 Hadron thermodynamics and chemistry]

Deepali Sharma (Weizmann)

“Probing Nuclear Matter With Jets and gamma-Hadron Correlations:Results from PHENIX”

[Tues.24-May-2011 17:00 Parallel 2-1 Jets]

Nathan Grau (Columbia)

“Identified particle v_3 measurements at 200GeV Au+Au collisions at RHIC-PHENIX experiment”

[Mon.24-May-2011 17:20-19:30 Poster Session 1 + Wine and cheese]

Sanshiro Mizuno (Univ. of Tsukuba)

“Measurements of low mass dielectrons in Au+Au collisions with the HBD upgrade of the PHENIX detector”

[Thur.26-May-2011 16:00 Parallel 5-3 Electromagnetic probes]

Mihael Makek (Weizmann)

“Direct photon production in heavy ion collisions in PHENIX experiment at RHIC”

[Thur.26-May-2011 16:40 Parallel 5-3 Electromagnetic probes]

Edouard Kistenev (BNL Phys.)

“Collision energy dependence of the flow and spectra results in Au+Au collisions at $\sqrt{s_{NN}}=7.7-200$ GeV from PHENIX”

[Fri.27-May-2011 17:50-18:10 Parallel 5-4 Global and collective dynamics]

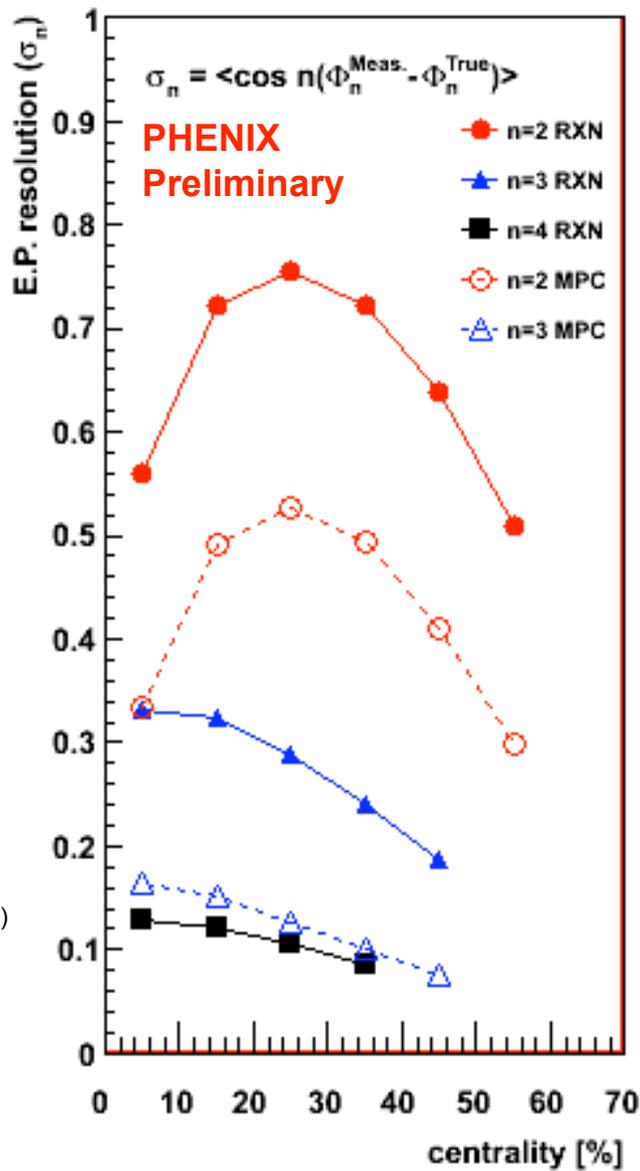
Xiaoyang Gong (Stony Brook Chem.)

Summary and Outlook

- ◆ Significant higher order event anisotropy observed
 - Consistent with initial geometrical fluctuation
 - Break degeneracy: Glauber & $4\pi\eta/s=1$ favored
 - Strong impact on Mach cone and ridge
- ◆ Almost perfect fluidity from 39GeV to 2.76TeV
- ◆ Direct photon v_2 observed
 - Small at high p_T --> consistent with pQCD
 - Large in low p_T --> challenge to theory

Backup slides

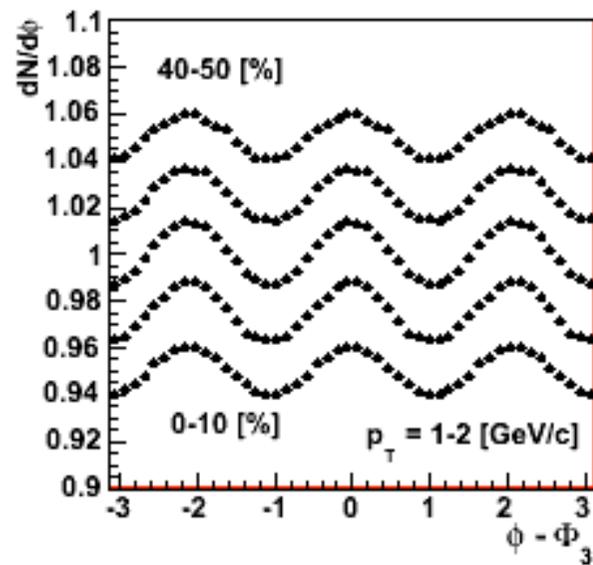
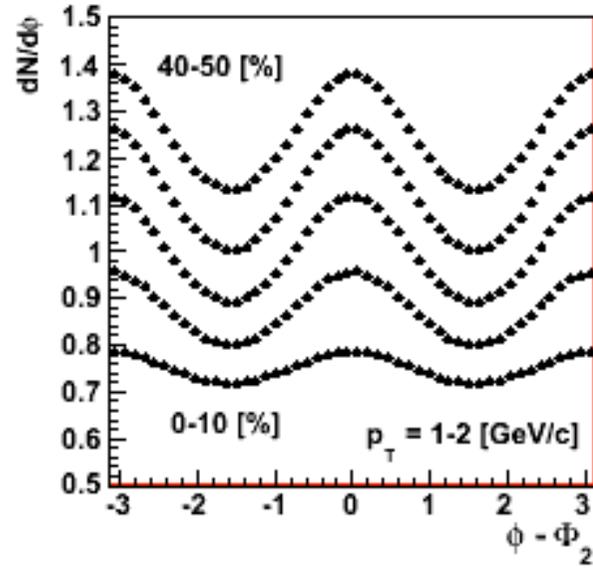
Event plane resolution and raw $\phi^{\text{track}} - \Phi_n^{\text{R.P.}}$ distribution



estimated from

RXN^(S) - RXN^(N)
 $|\eta| = 1 \sim 2.8$
 $\Delta\eta = 2$

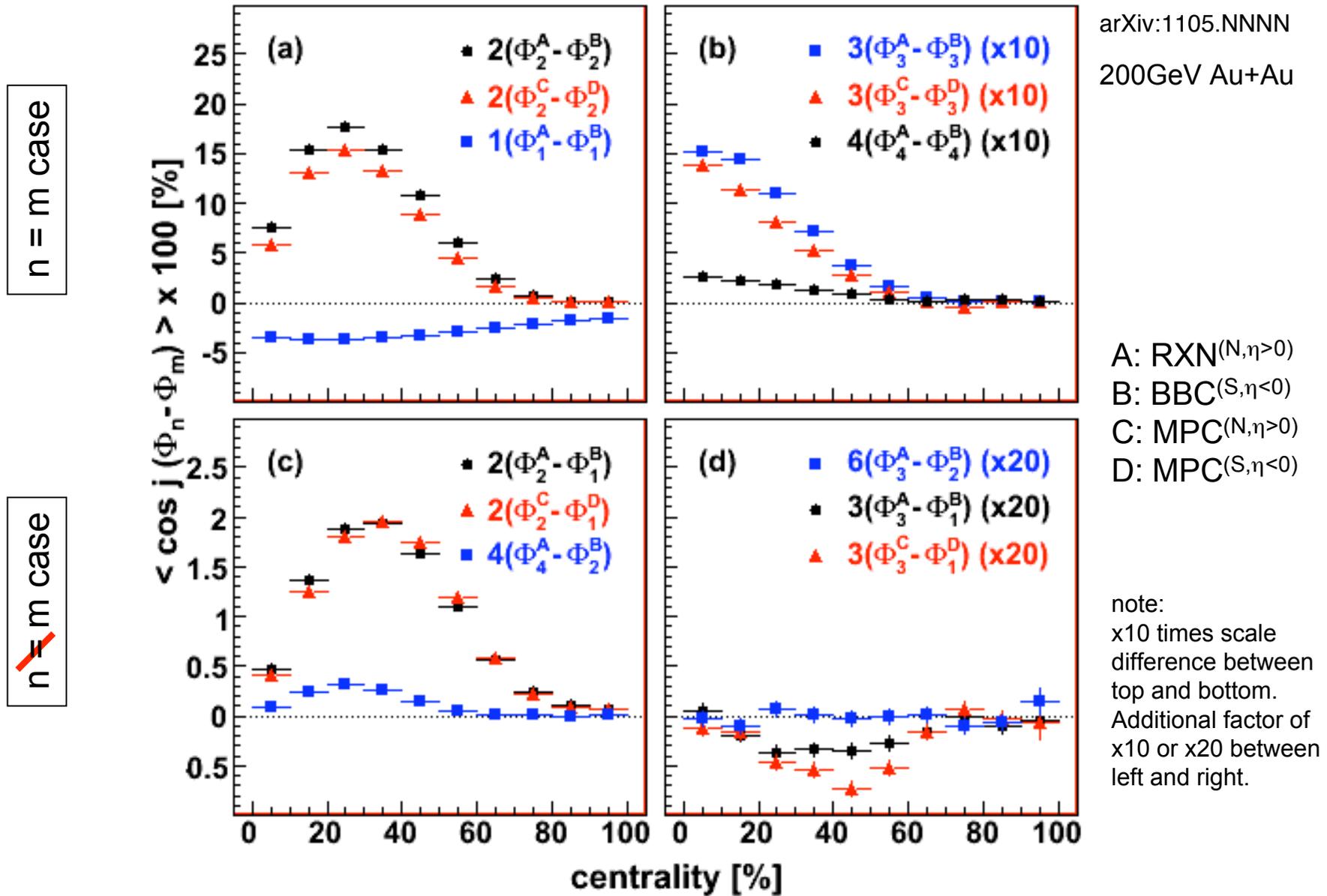
MPC^(S) - MPC^(N)
 $|\eta| = 3.1 \sim 3.7$
 $\Delta\eta = 6.2$



200GeV Au+Au

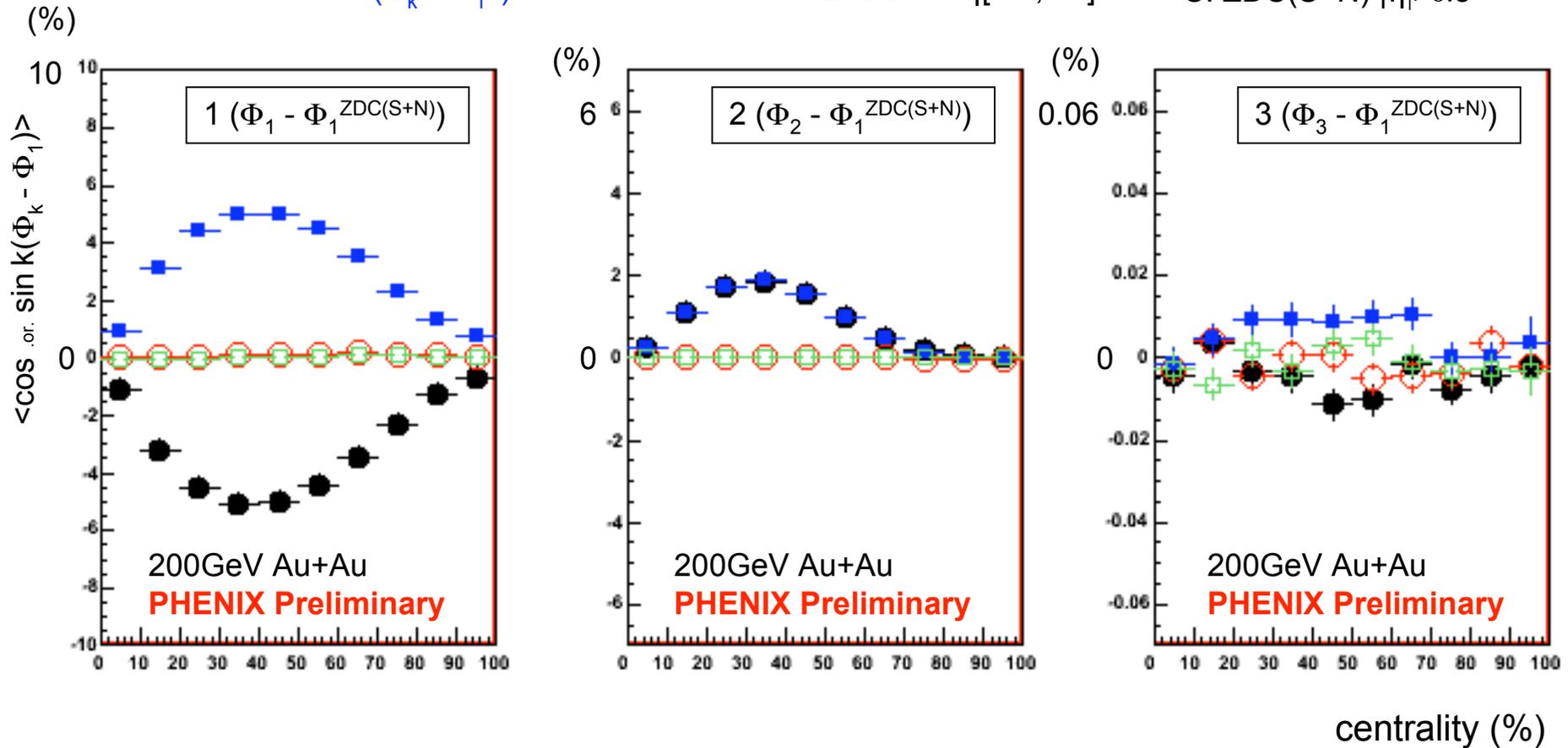
Φ_2 , Φ_3 and Φ_4 are defined for each event.

Event plane correlation between the same or different harmonics

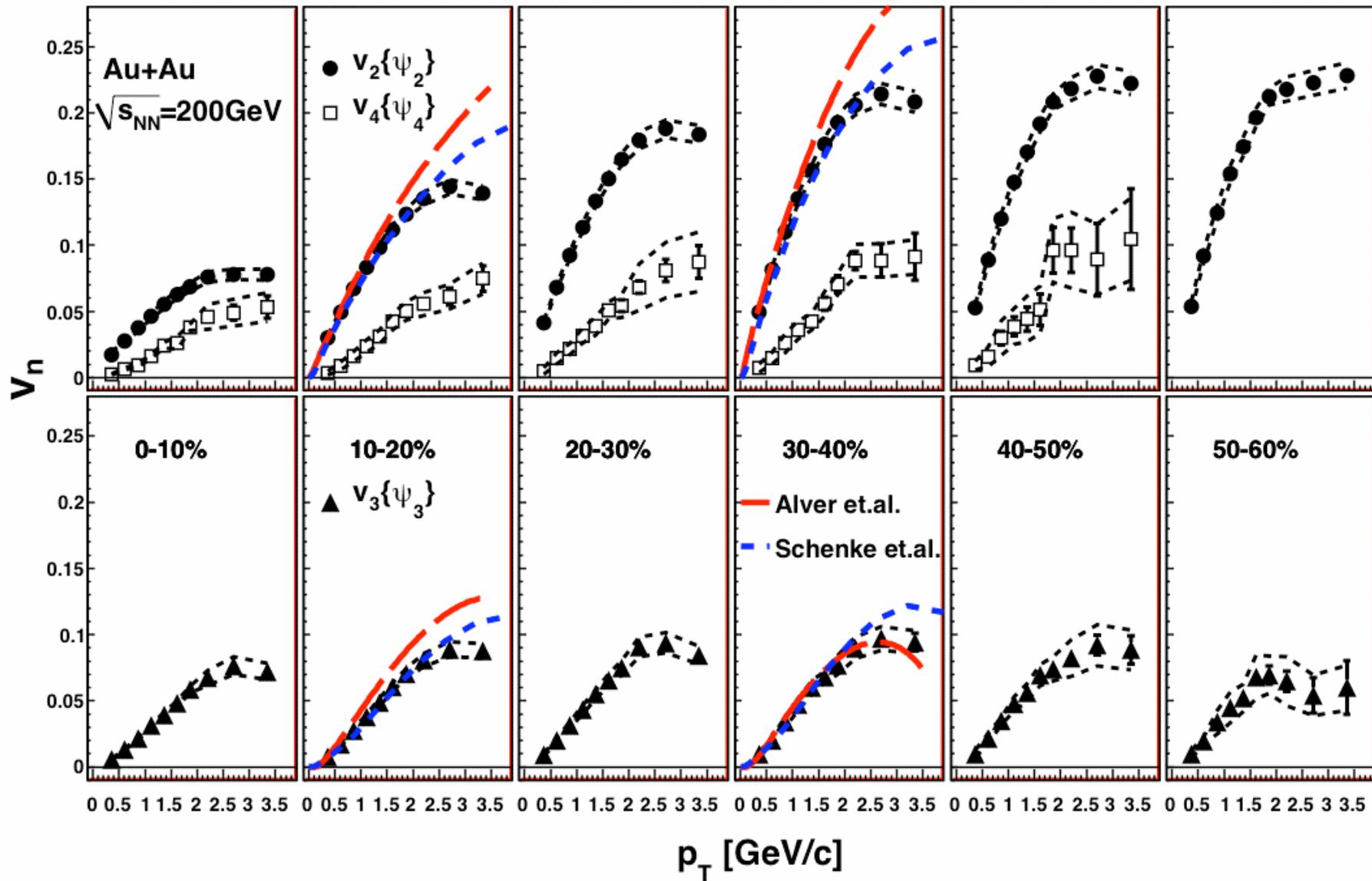


Correlation between different harmonics (w.r.t spectator Φ_1^{ZDC})

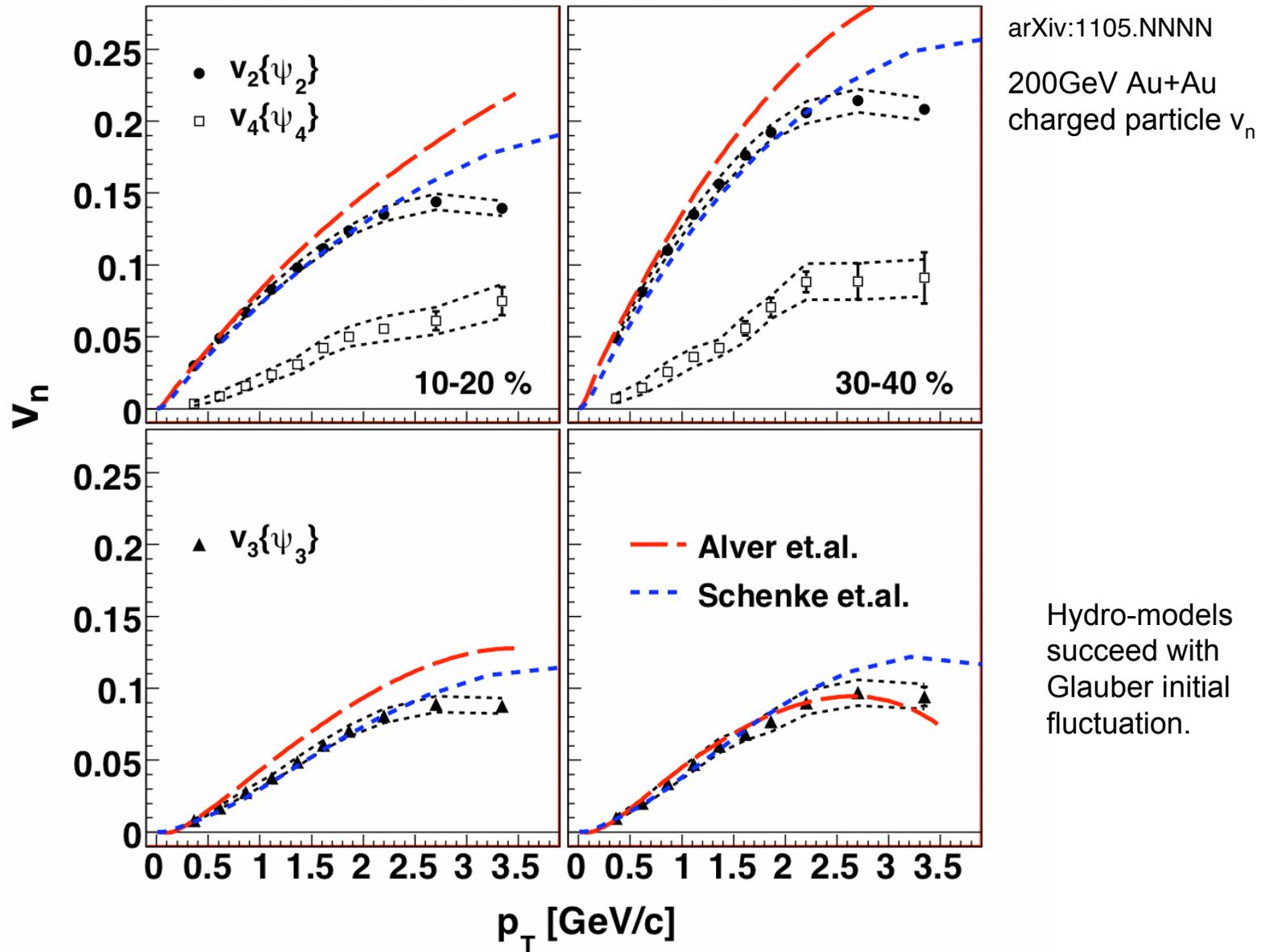
● $\langle \cos k(\Phi_k^{\text{A}} - \Phi_1^{\text{C}}) \rangle$ ○ sin term A: BBC^(S) $\eta[-3.9,-3.1]$ (N-side flipped to combine)
 ■ $\langle \cos k(\Phi_k^{\text{B}} - \Phi_1^{\text{C}}) \rangle$ □ sin term B: BBC^(N) $\eta[3.1,3.9]$ C: ZDC(S+N) $|\eta|>6.5$

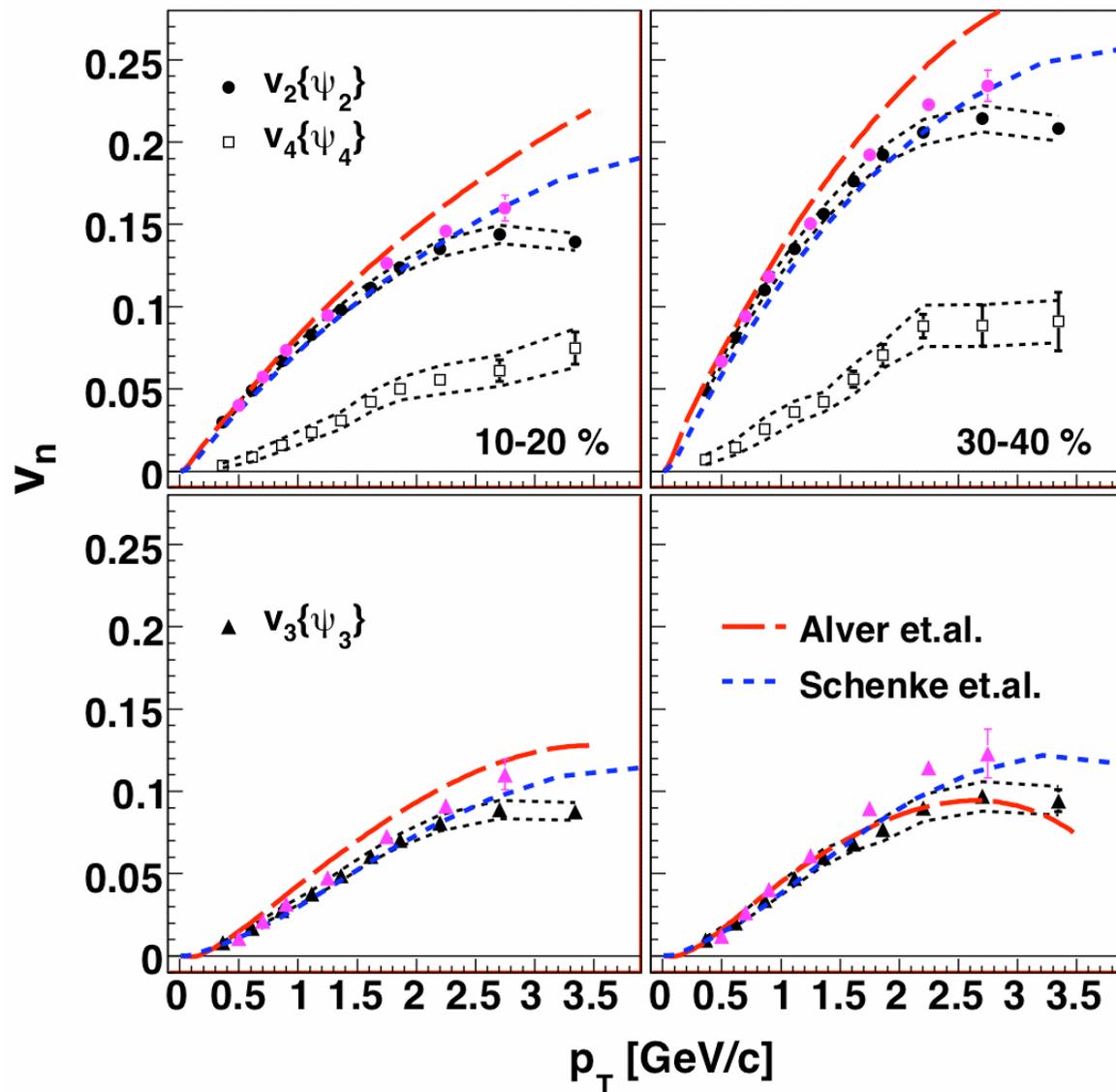


clear sign-flipping in v_1 , clear positive v_2
 indication of sign-flipping in v_3 , $\text{sign}(v_1) = \text{sign}(v_3)$



comparison with theory calculations at 200GeV Au+Au

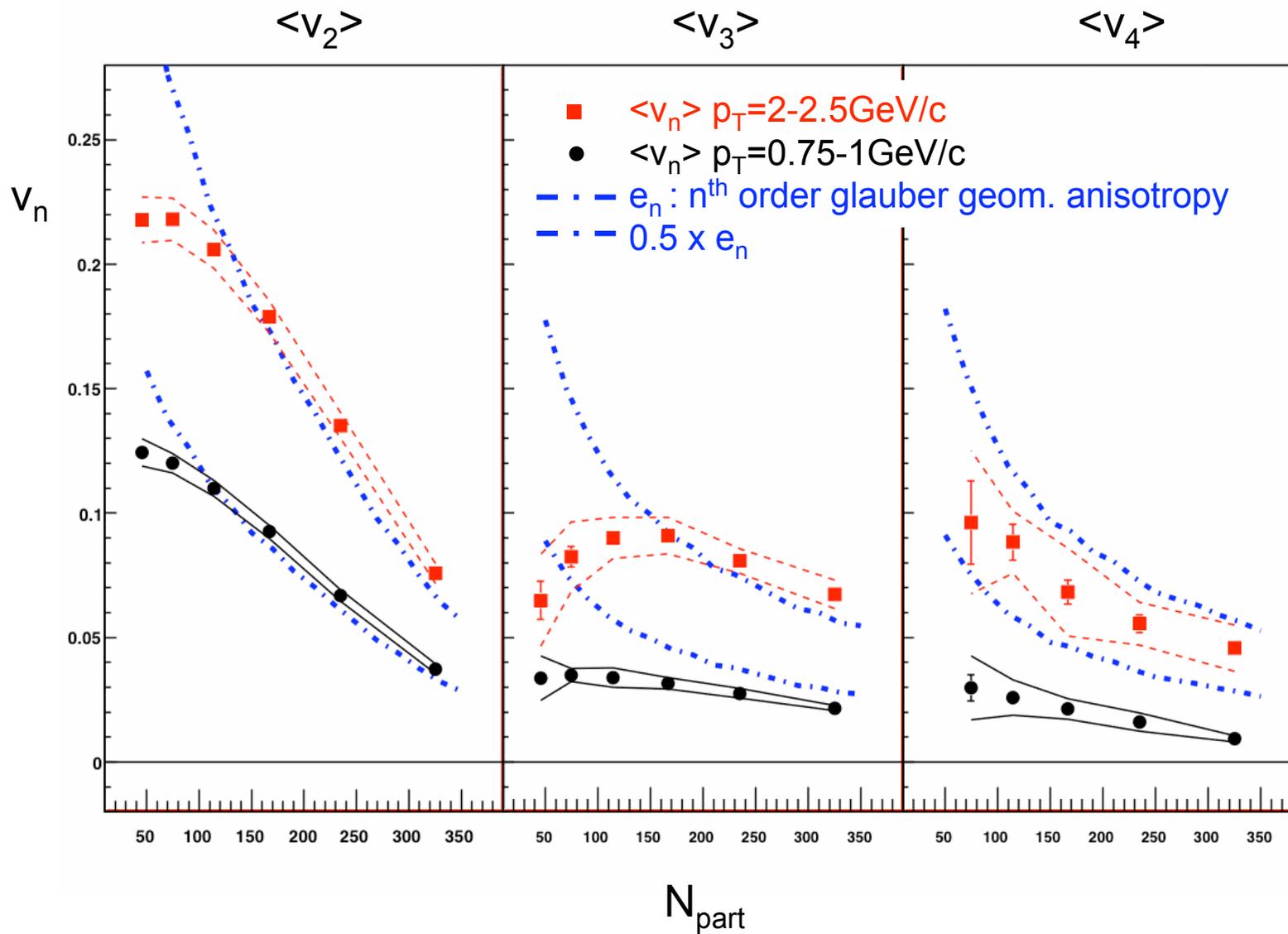




2-particle correlation within
 central arm $|\Delta\eta| < 0.35$
 also gives similar v_2 and v_3
 with some small increase at
 higher p_T from non-flow jet
 bias ($|\Delta\eta| = 0.3 \sim 0.7$)

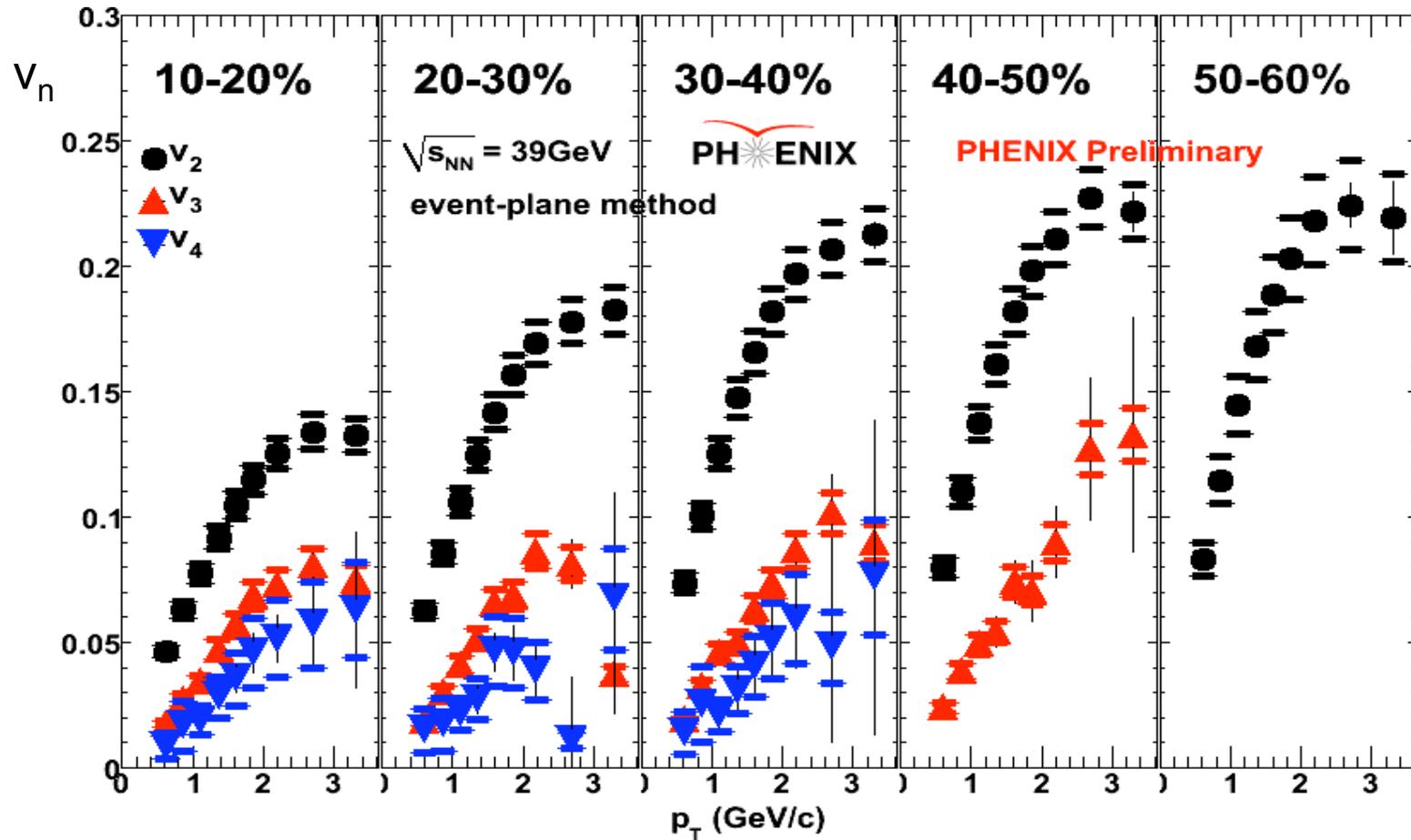
PHENIX preliminary
 with central-central
 2-particle-correlation
 at $|\Delta\eta| > 0.3$

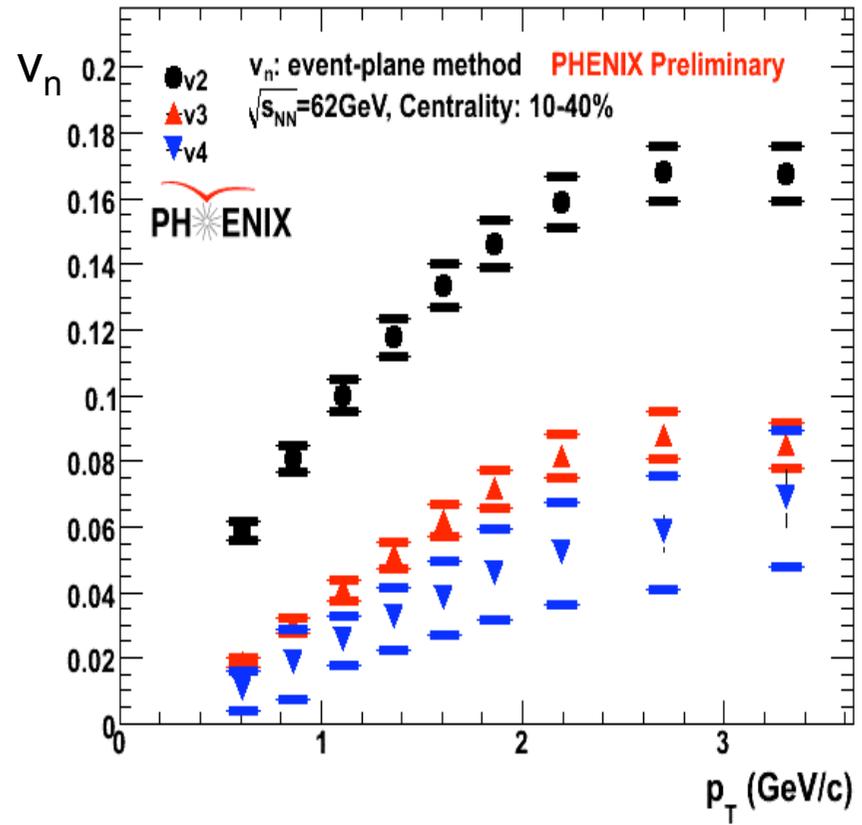
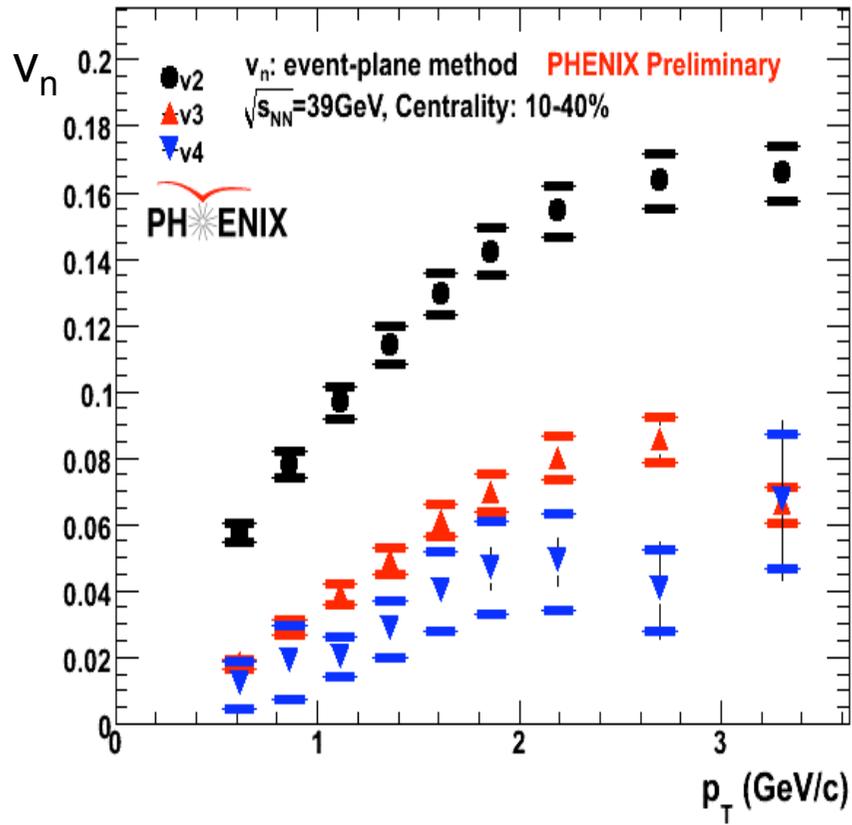
B. Alver et. al., Phys. Rev. C82, 034913(2010).
 B. Schenke et. al., Phys. Rev. Lett. 106, 042301(2011).

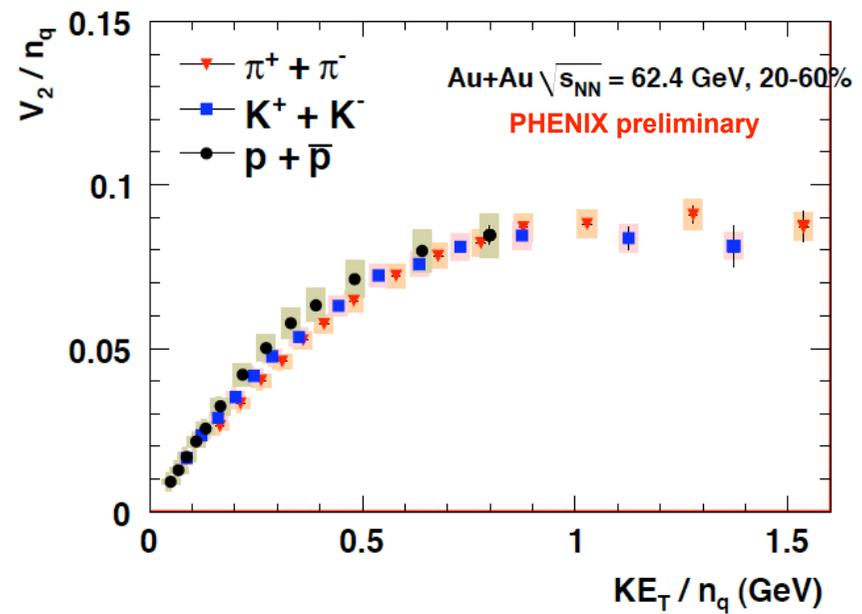
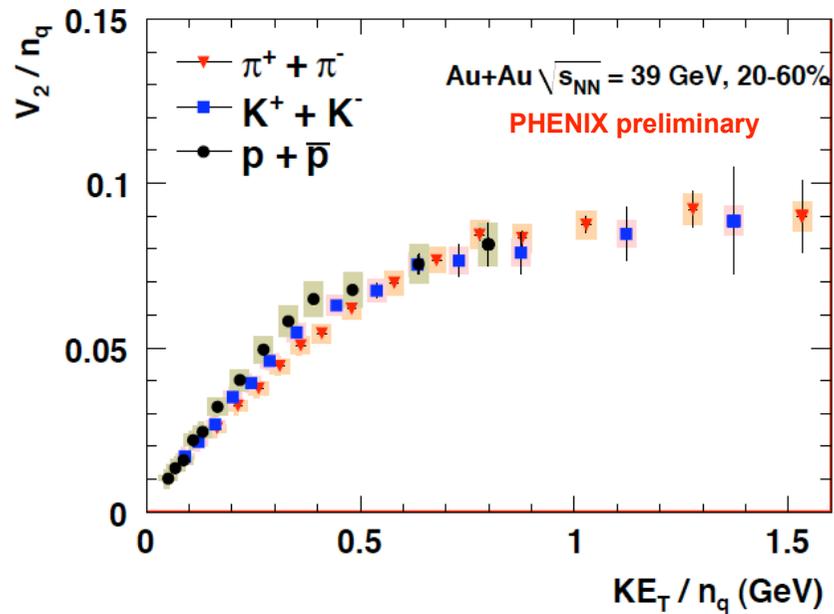
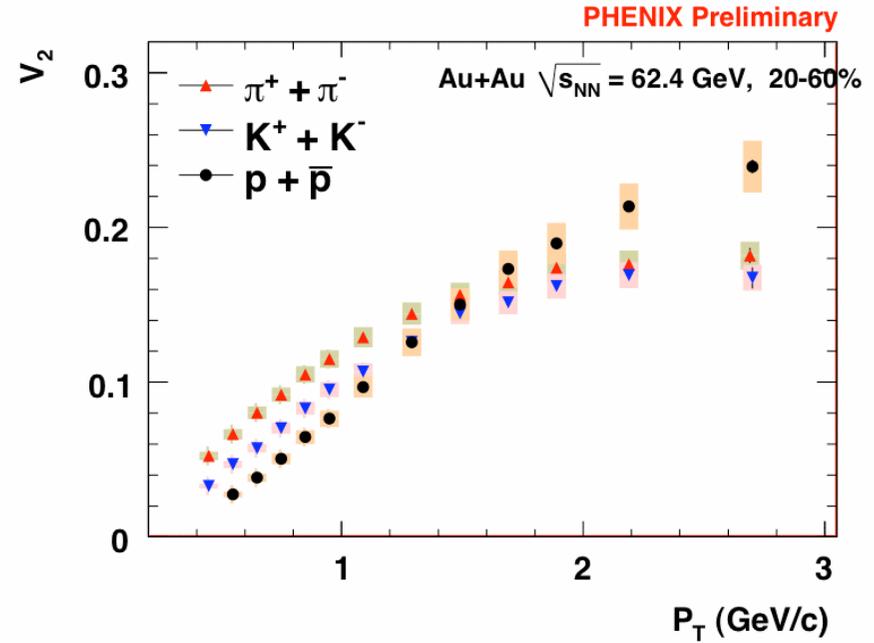
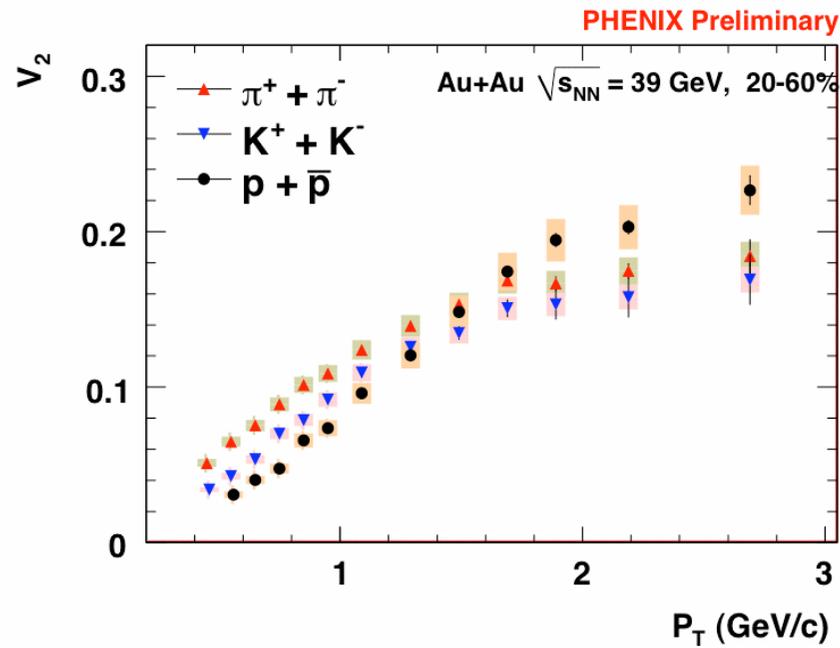


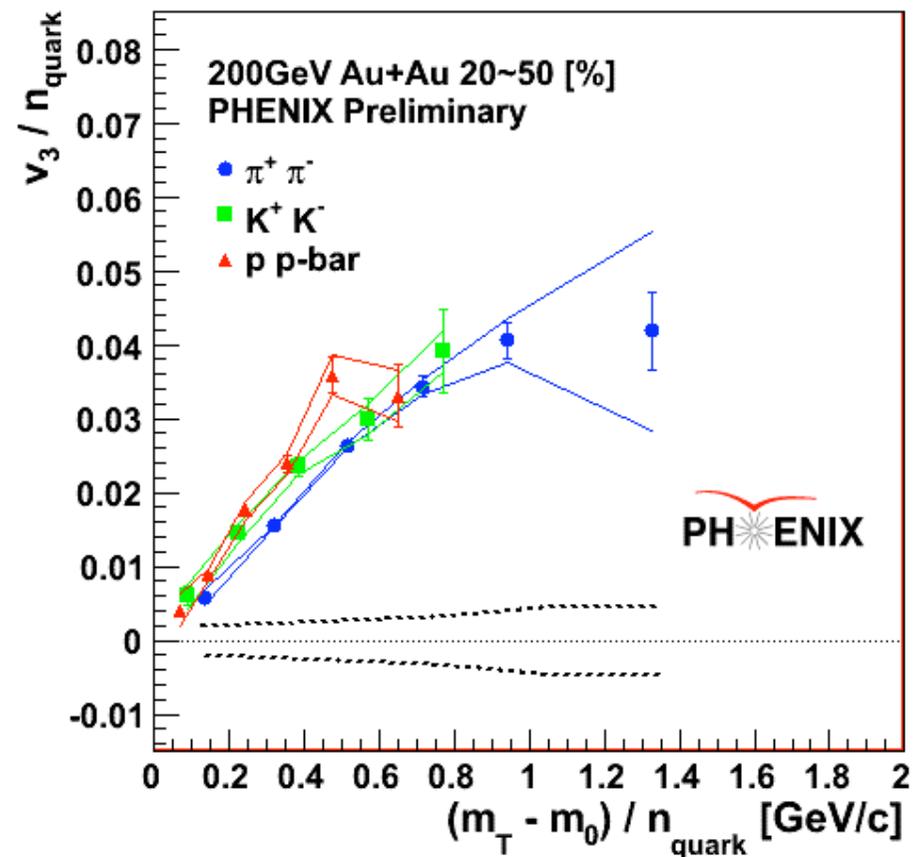
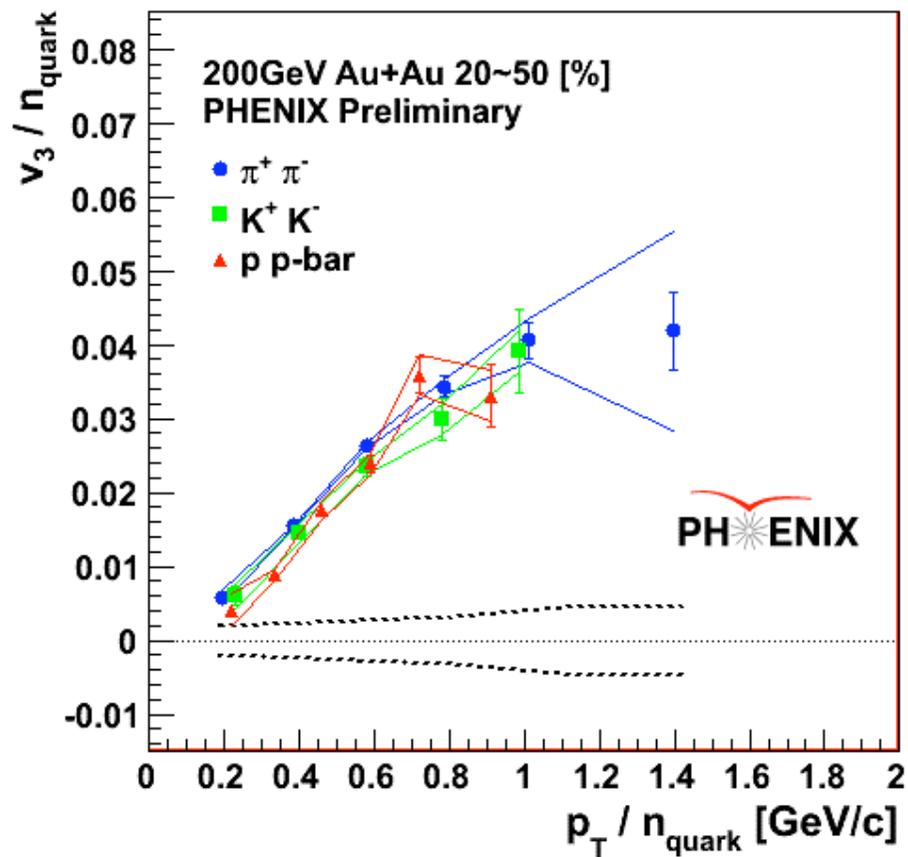
$v_2\{\Phi_2\}, v_3\{\Phi_3\}, v_4\{\Phi_4\}$ at 39GeV Au+Au

charged particle $v_n : |\eta| < 0.35$
 reaction plane $\Phi_n : |\eta| = 1.0 \sim 2.8$









Method of event plane determination

(1) Detector calibration / cell-by-cell calibration

(2) Q-vector, re-centering, normalization of width

$$Q_{\{n\}x} = \sum_i \{ w_i \cos(n \phi_i) \} \quad Q'_{\{n\}x} = (Q_{\{n\}x} - \langle Q_{\{n\}x} \rangle) / \sigma_{Q_{\{n\}x}}$$

$$Q_{\{n\}y} = \sum_i \{ w_i \sin(n \phi_i) \} \quad Q'_{\{n\}y} = (Q_{\{n\}y} - \langle Q_{\{n\}y} \rangle) / \sigma_{Q_{\{n\}y}}$$

$$Q_{\{1\}x}^{\text{ZDC}} = \sum_i \{ w_i x_i \} / \sum_i \{ w_i \}$$

$$Q_{\{1\}y}^{\text{ZDC}} = \sum_i \{ w_i y_i \} / \sum_i \{ w_i \}$$

(3) n-th harmonics reaction plane

$$\Phi_{\{n\}} = \text{atan2}(Q'_{\{n\}y}, Q'_{\{n\}x}) / n$$

(4) Fourier flattening (Sergei's+Art's method paper)

$$n \Phi'_{\{n\}} = n \Phi_{\{n\}} + \sum_i (2/i) \{ - \langle \sin(i n \Phi_{\{n\}}) \rangle \cos(i n \Phi_{\{n\}}) + \langle \cos(i n \Phi_{\{n\}}) \rangle \sin(i n \Phi_{\{n\}}) \}$$

(5) measure v_n w.r.t. Φ_n and correct for E.P. resolution

2-particle correlation among 3-sub detectors

Forward^{Hit} (F), Backward^{Hit} (B), Central^{Track} (C)

(1) measure $d\phi$ distribution between 2 detectors weighting by the hit amplitude

(2) normalize by the event mixing to make correlation functions for 3 combinations

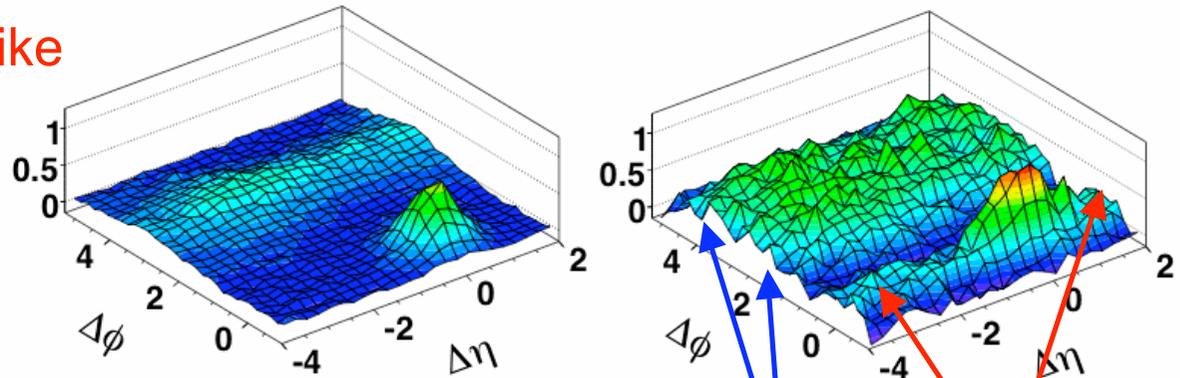
(3) fit the correlation with Fourier function to extract $v_n^F v_n^B$, $v_n^F v_n^C$ and $v_n^B v_n^C$

(4) $v_n^F(\text{Hit})$ and $v_n^B(\text{Hit})$ can be determined as a function of centrality

(5) $v_n^C(\text{Track})$ can be determined as a function of centrality and p_T

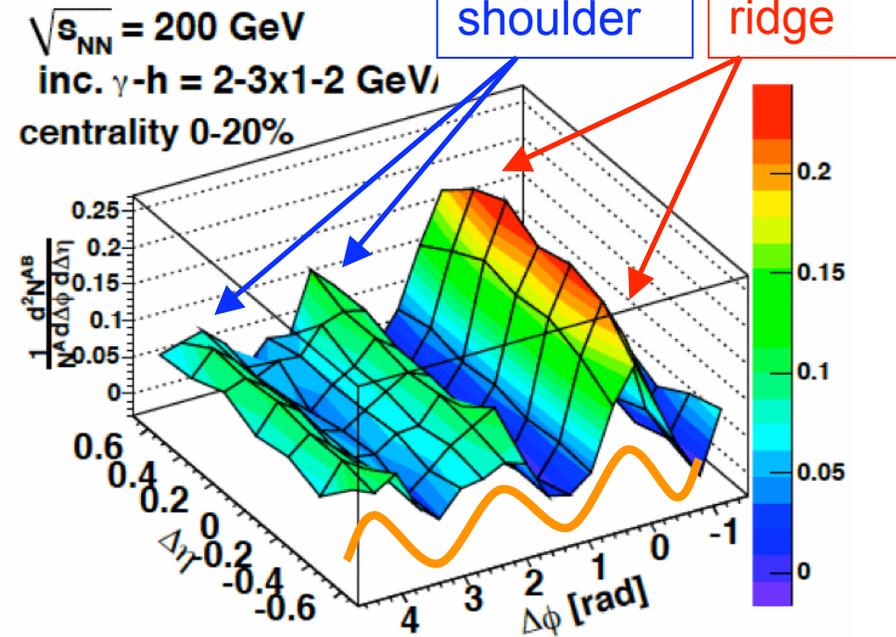
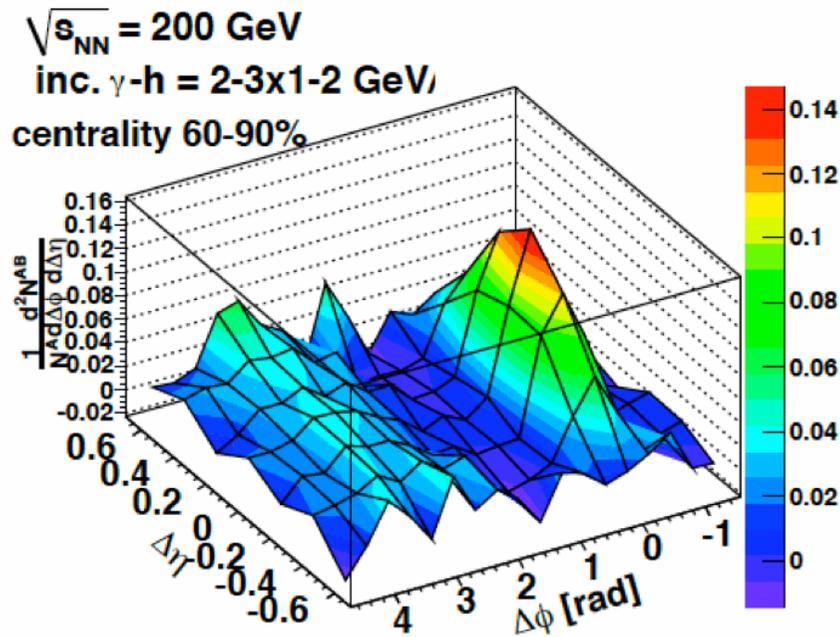
Some couplings between “mach-cone-like and ridge-like emissions” and v_3 are expected to be there!

What is the origin and what is the consequence?

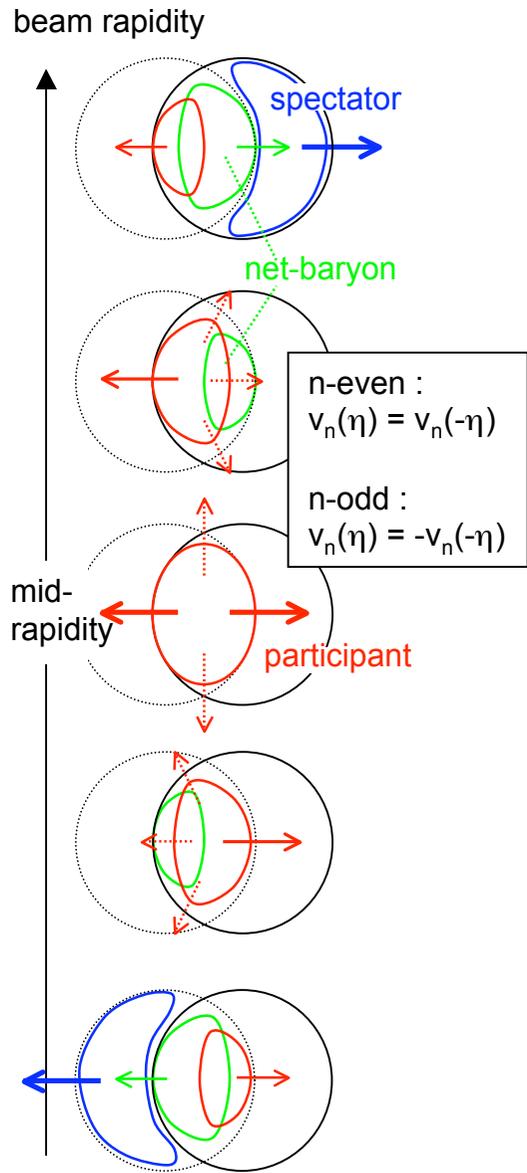


(a) p+p PYTHIA (version 6.325)

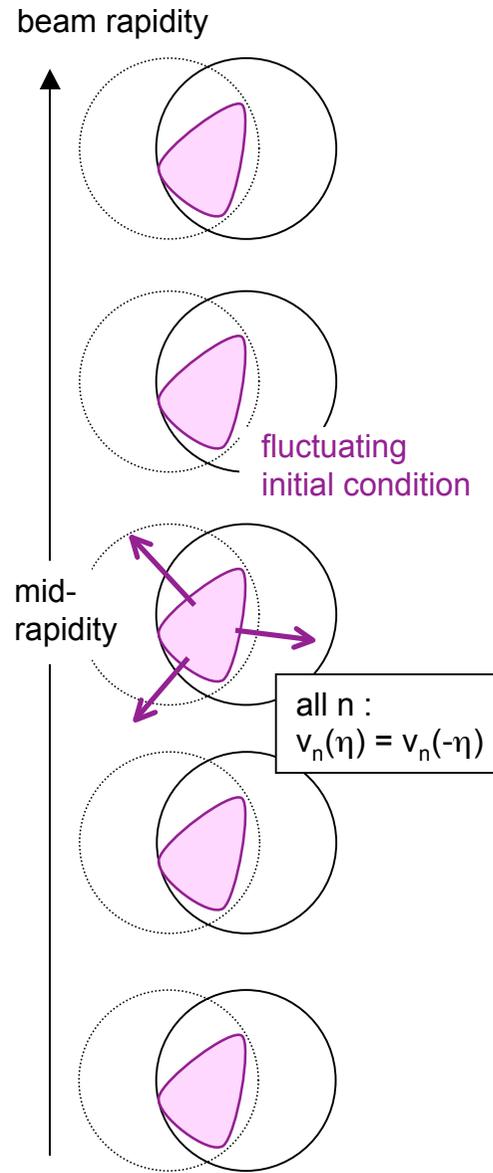
(b) Au+Au 0-30% (PHOBOS)



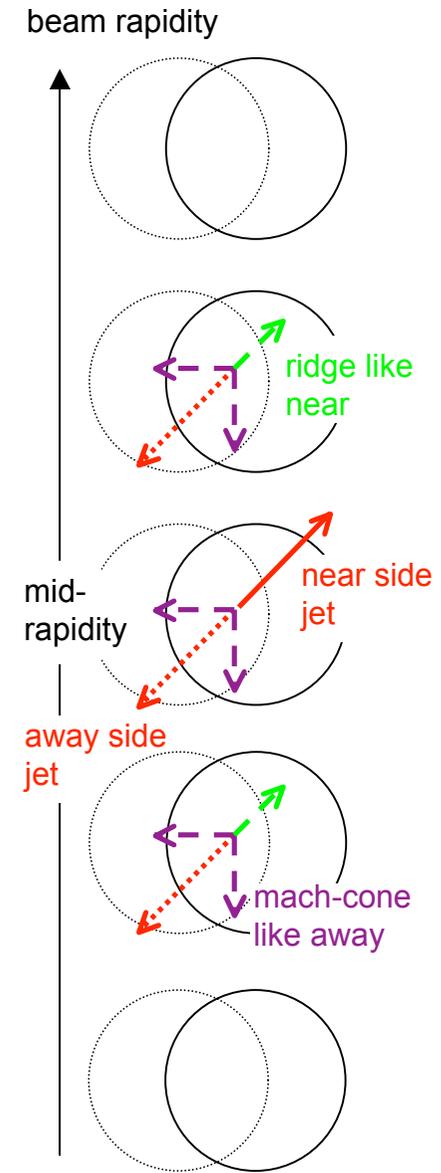
case1



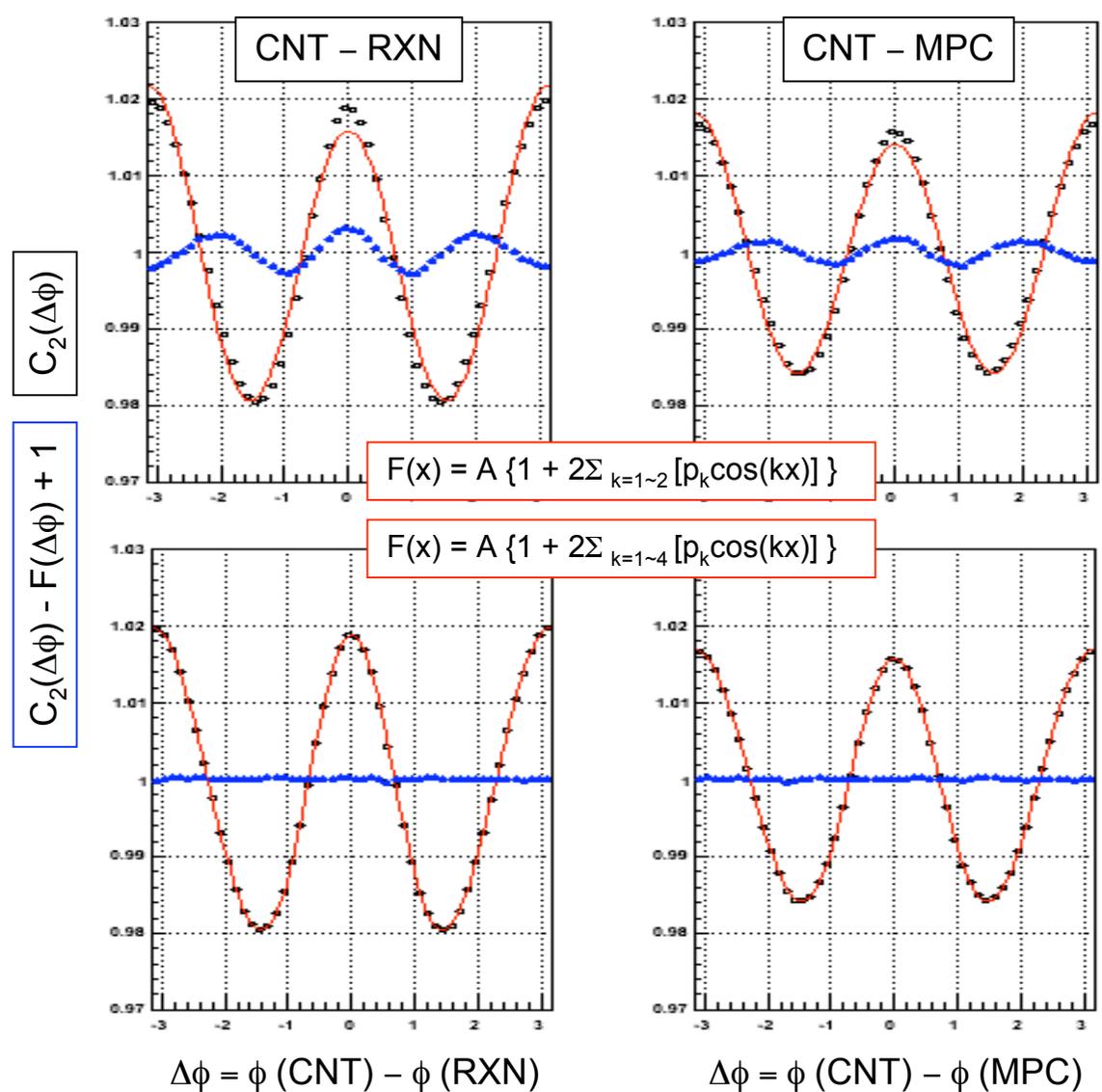
case2



case3



2-part. correlation between central and forward



200GeV Au+Au 20~30%
PHENIX Preliminary

CNT: central tracks
 mid-rapidity ($|\eta| < 0.35$)
 charged hadrons
 $p_T = 2 \sim 4$ (GeV/c)

RXN: reaction plane detector
 forward $|\eta| = 1.0 \sim 2.8$
 all cells/hits (charge weighting
 with Pb converter)

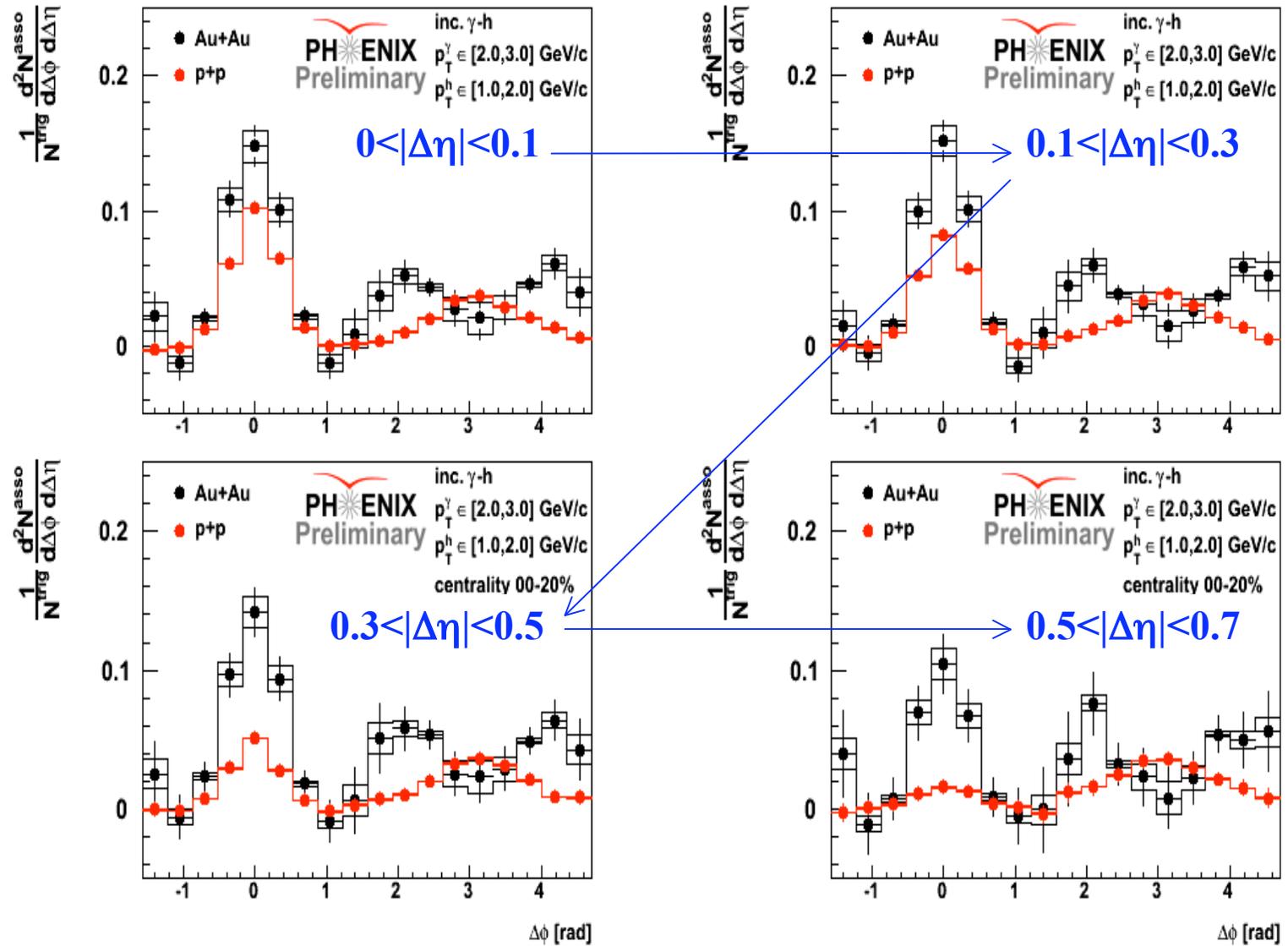
MPC: muon piston calorimeter
 forward EM-cal $|\eta| = 3.1 \sim 3.7$
 all cells/towers (eT weighting)

$$p_n = v_n^A \times v_n^B$$

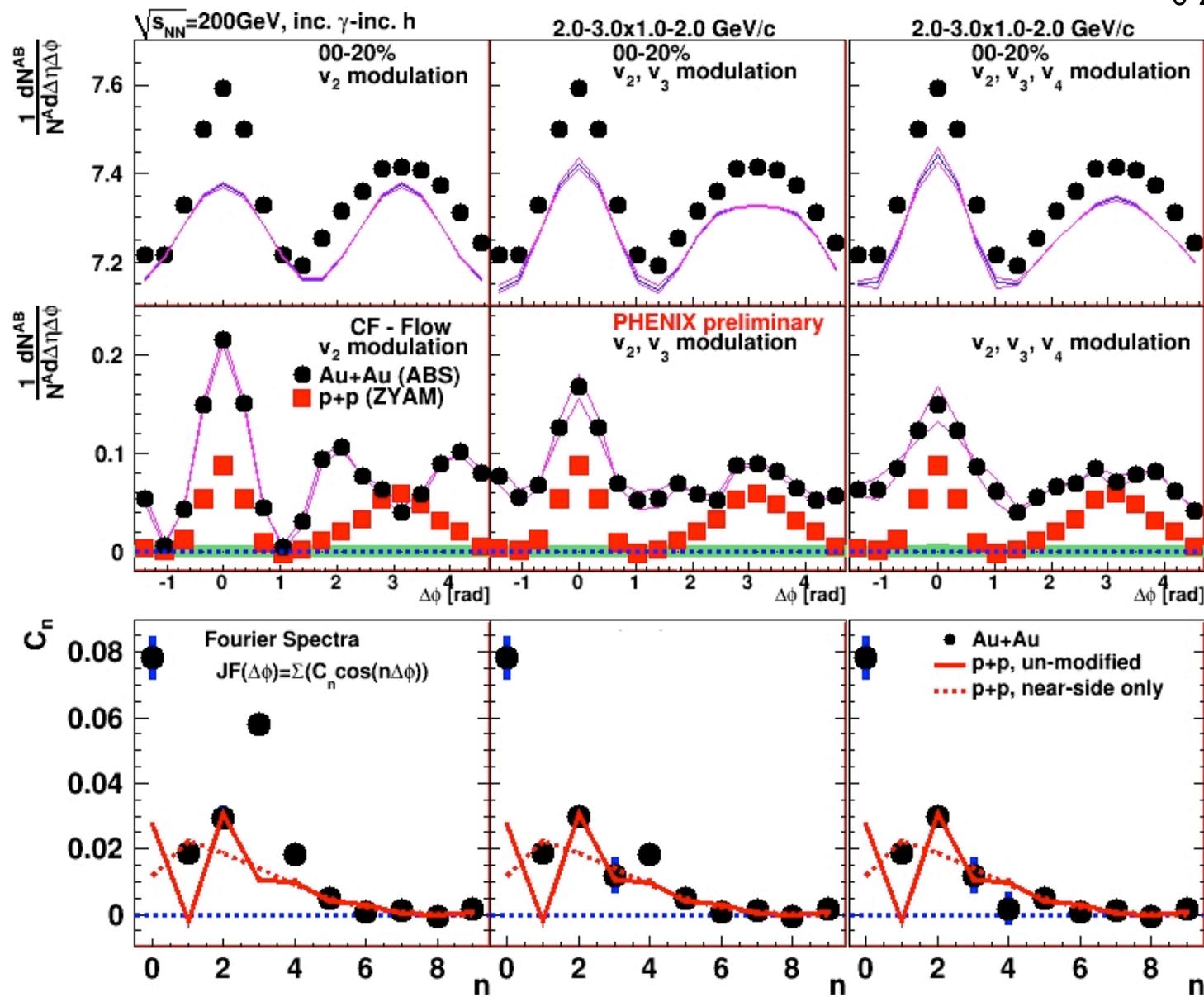
clear 3rd moment in
 two-particle correlation
 with large η gap

central-central 2-part. correlation with $\Delta\eta$ dependence

200GeV Au+Au
0-20%, inc. γ -had.

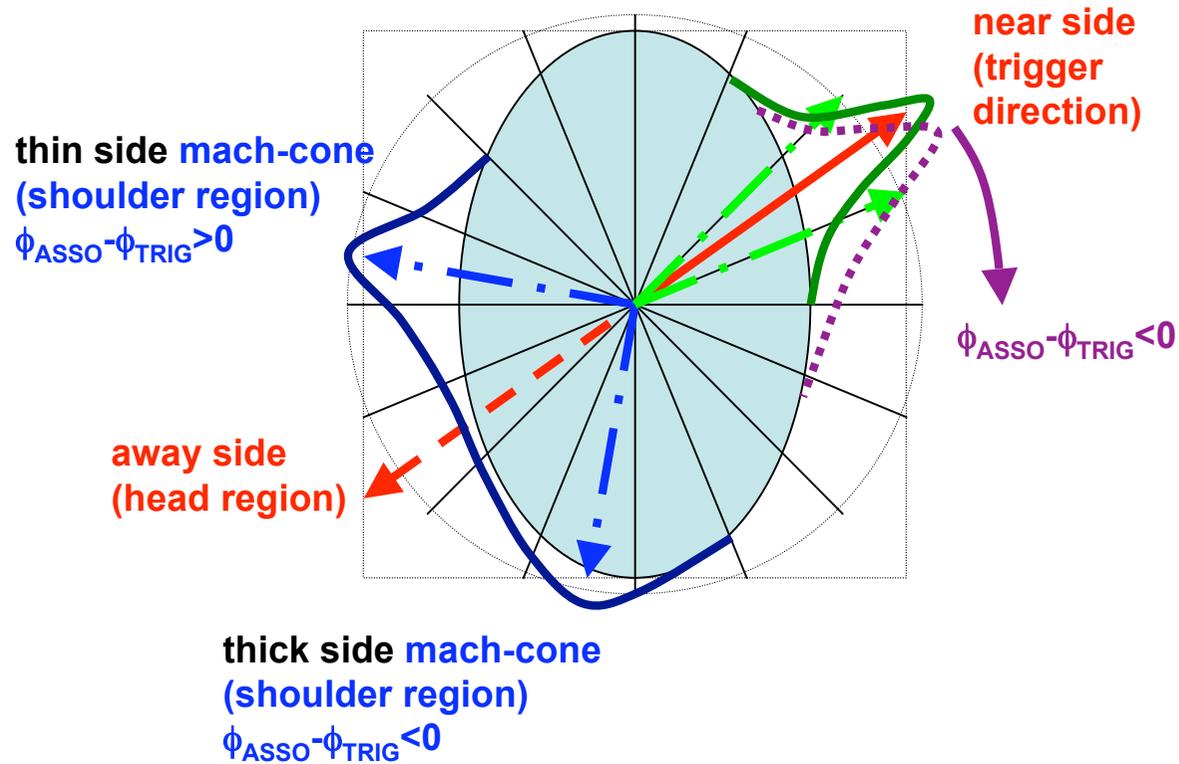


flow subtraction with measured v_n for cent-cent 2-par. correlation 200GeV Au+Au
 0-20%, inc. γ -had.

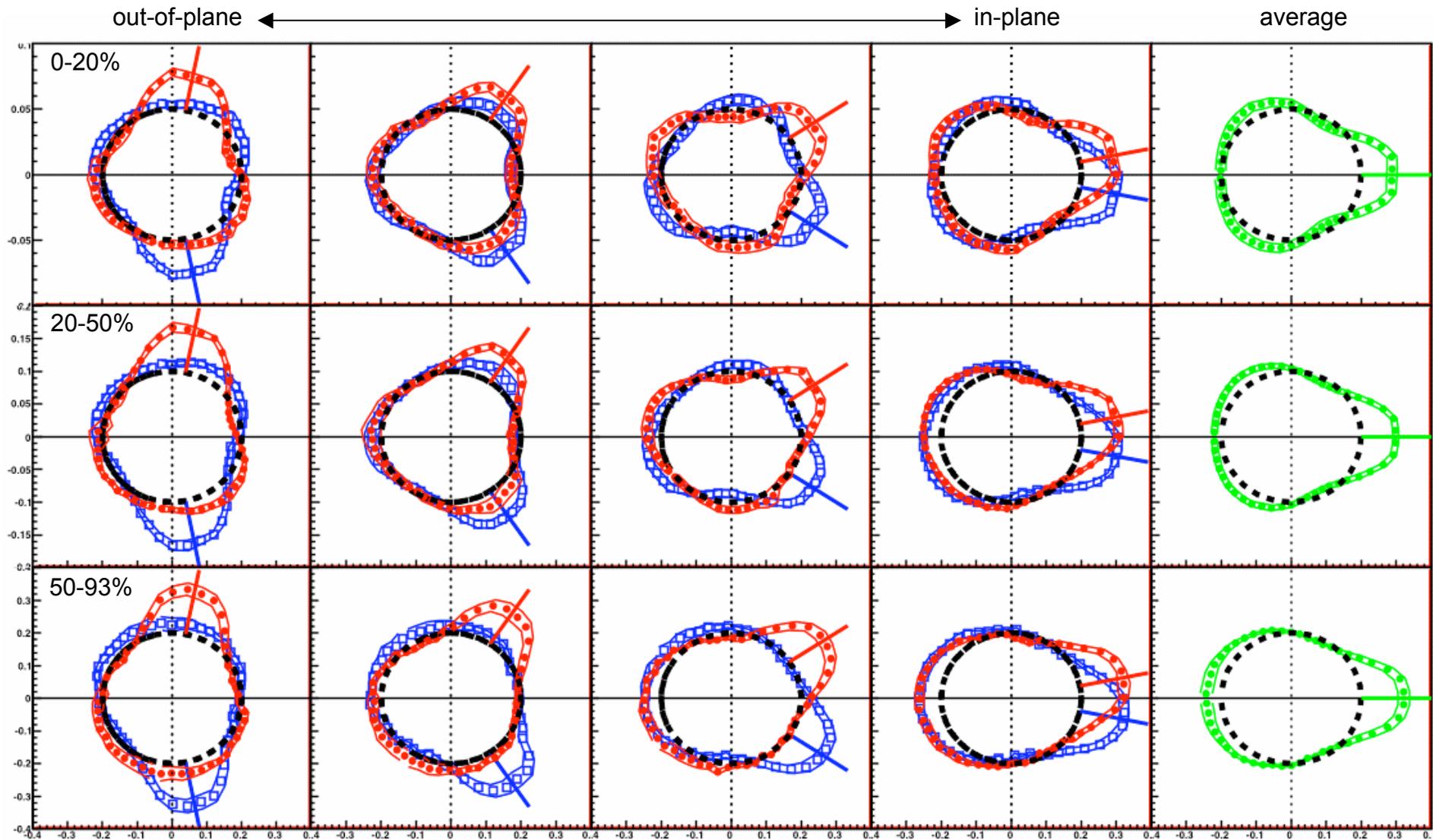


Fourier spectra of extracted jet shape

Probe the transverse geometry and/or dynamics
with trigger angle selected 2-particle correlation

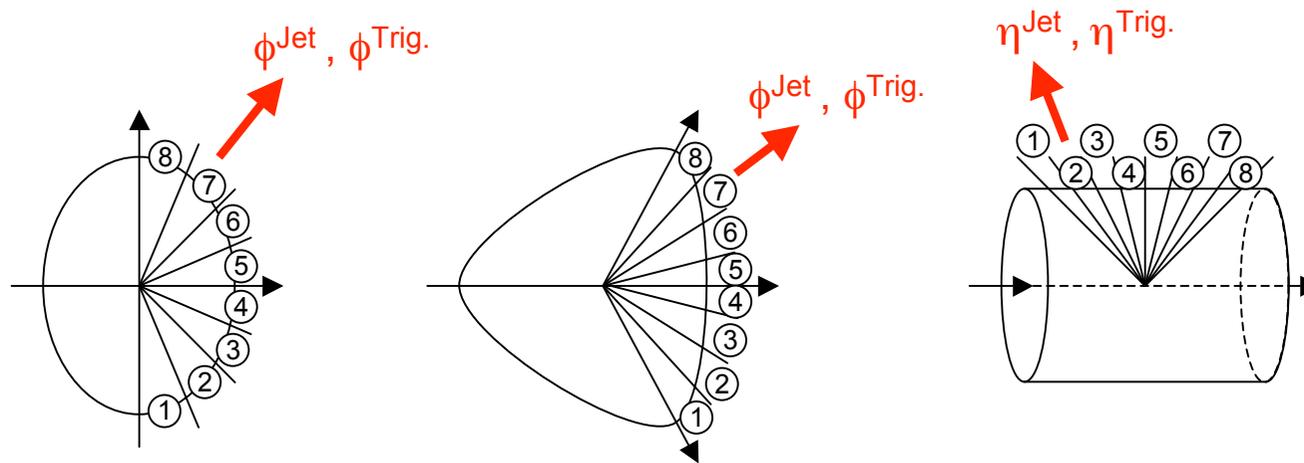


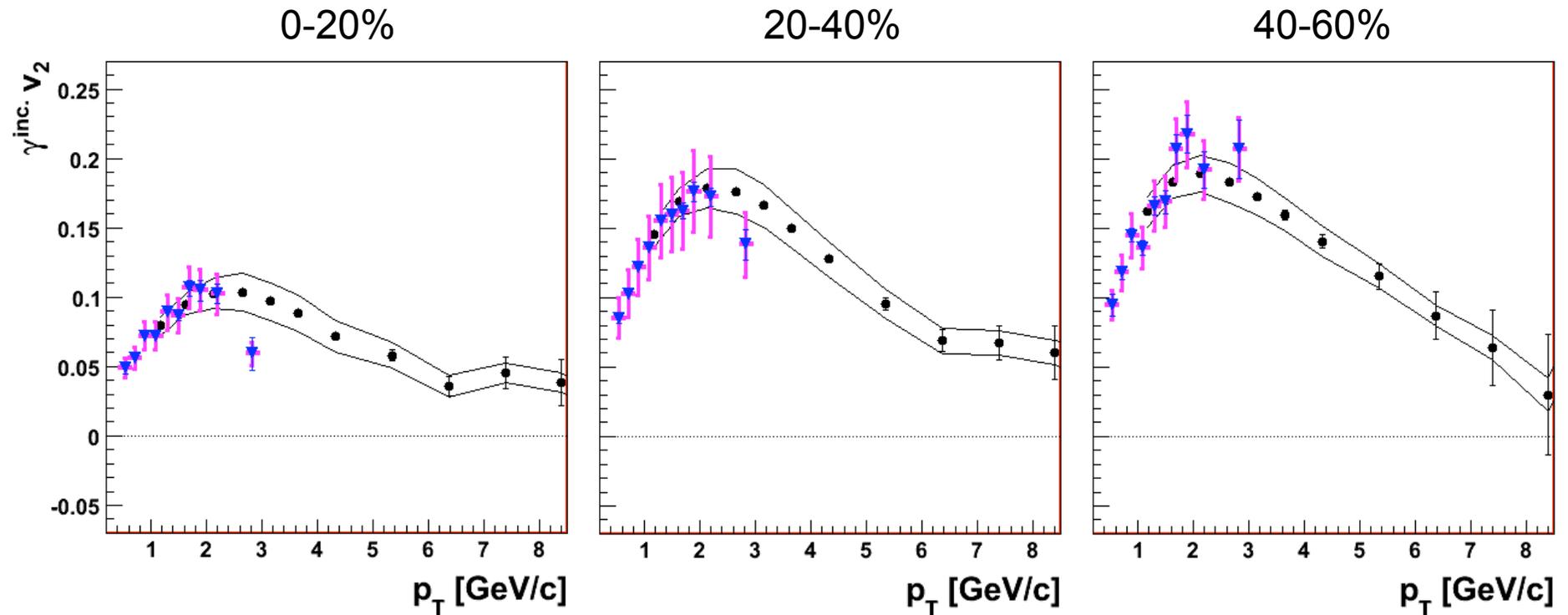
Flow subtracted 2-particle $\Delta\Phi$ correlation with trigger angle selection in 200GeV Au+Au

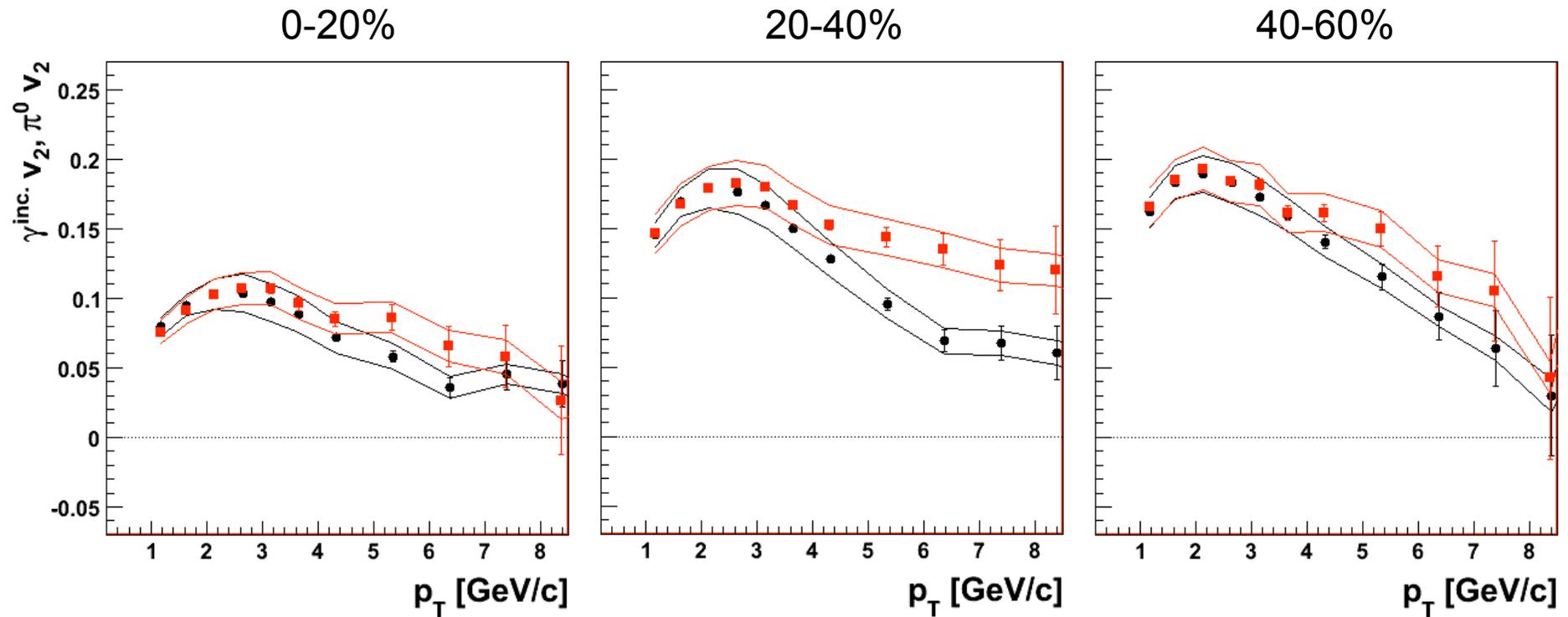


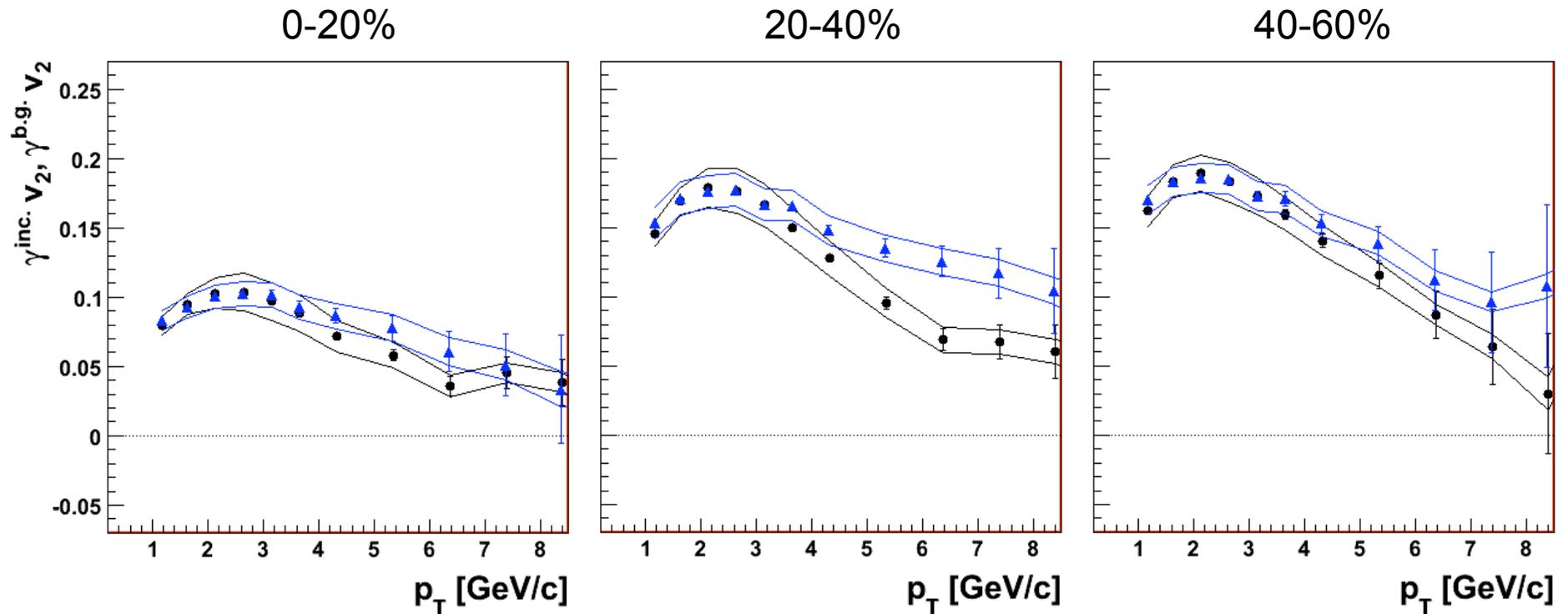
200GeV Au+Au \rightarrow h-h ($p_T^{\text{Trig}}=2\sim 4\text{GeV}/c$, $p_T^{\text{Asso}}=1\sim 2\text{GeV}/c$)
 $v_2(v_4\{\Phi_2\})$ -only subtraction **PHENIX preliminary**

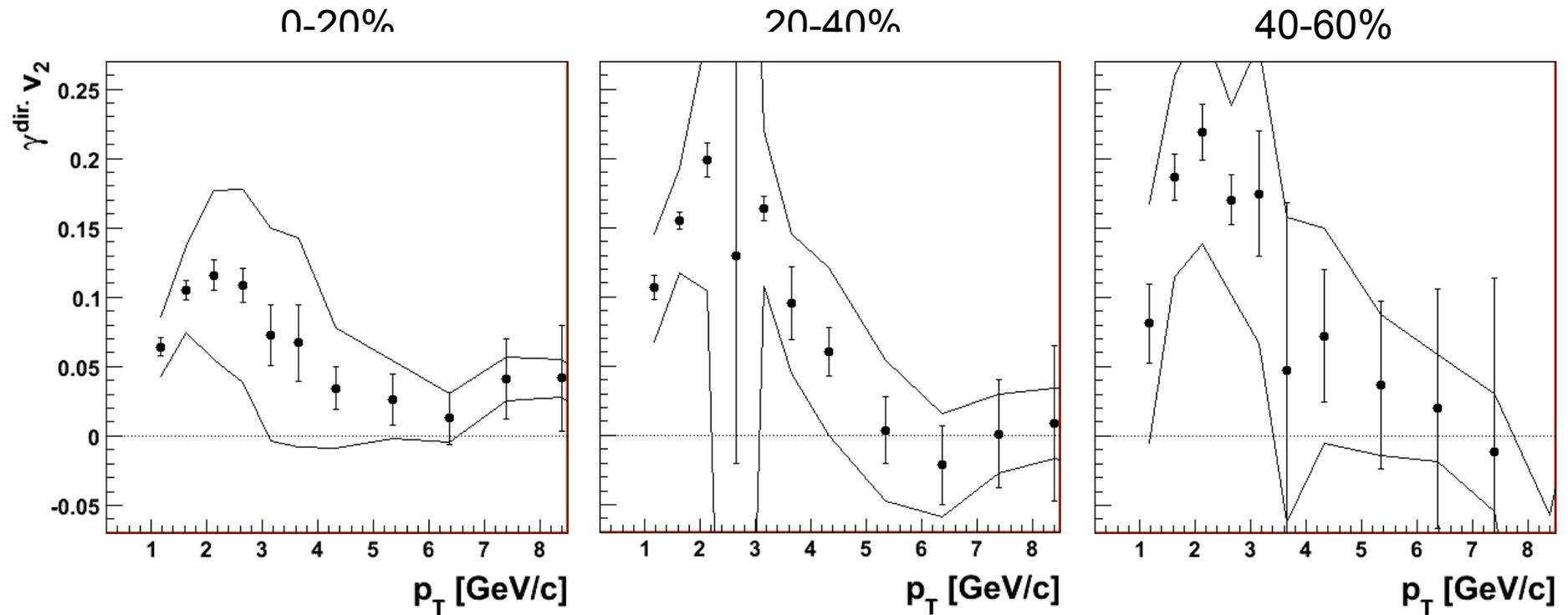
jet, di-jet and multi-particle correlation with various conditions



real photon v_2 and external conversion photon v_2 

Inclusive photon v_2 and $\pi^0 v_2$ 

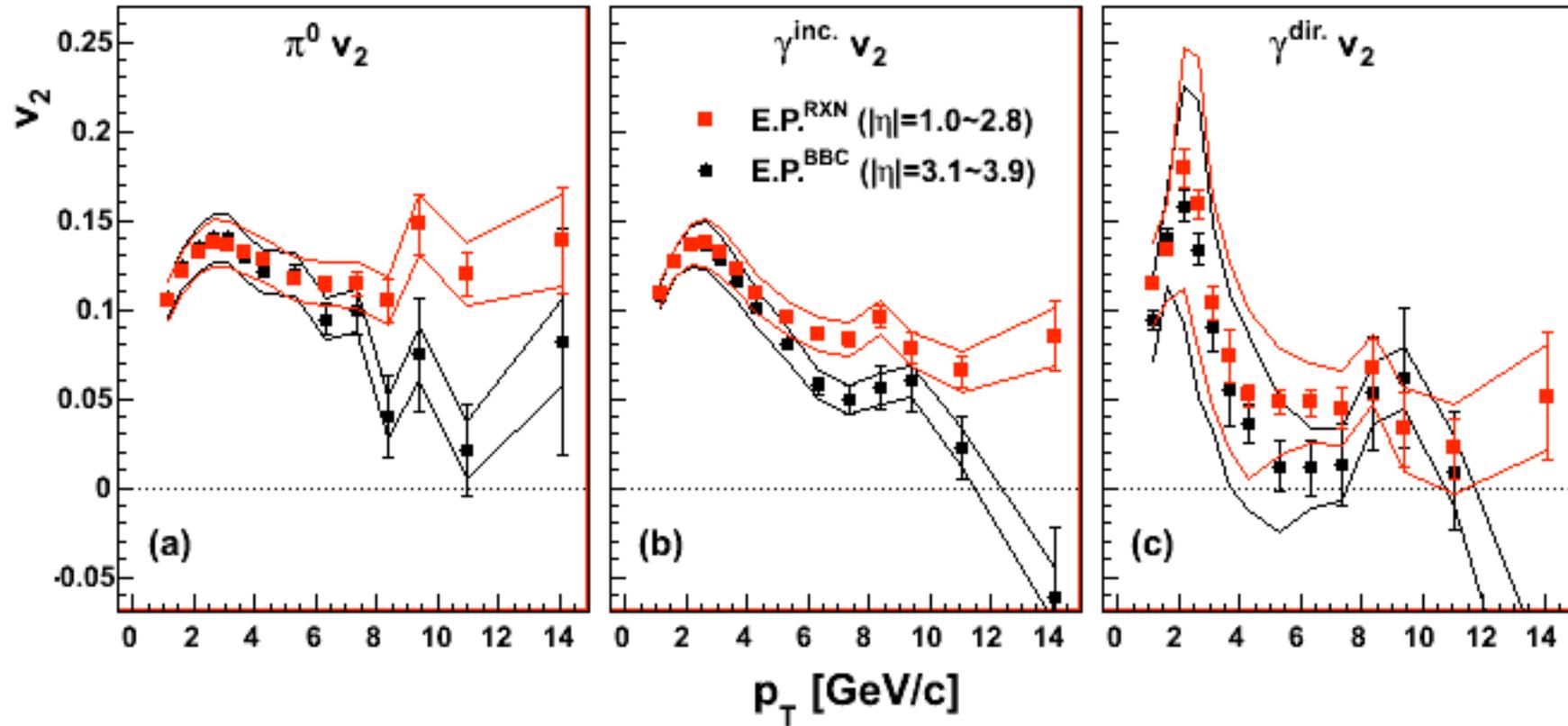
Inclusive photon v_2 and decay photon v_2 

direct photon v_2 

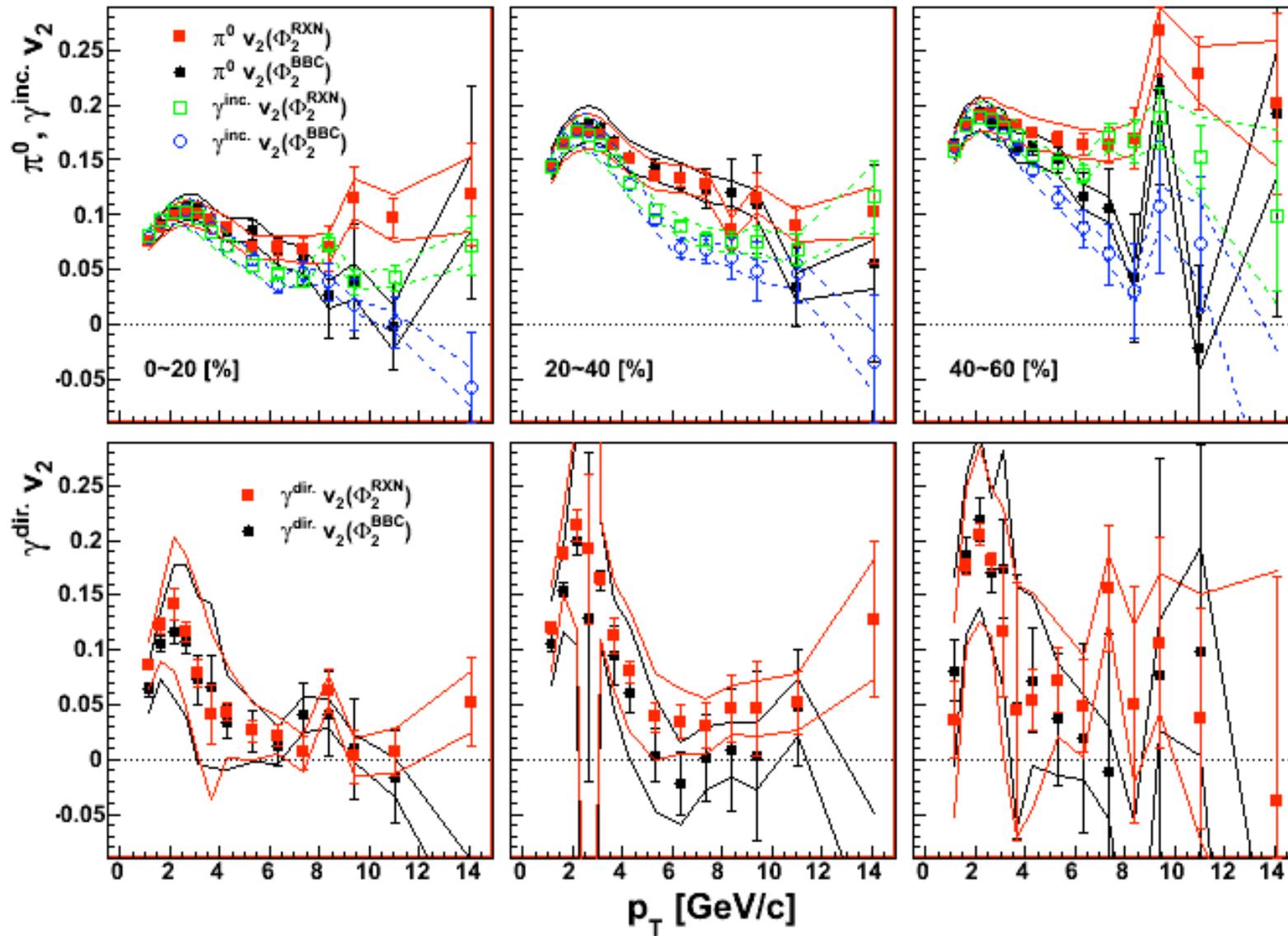
$\pi^0, \gamma^{\text{inclusive}}, \gamma^{\text{direct}} v_2$

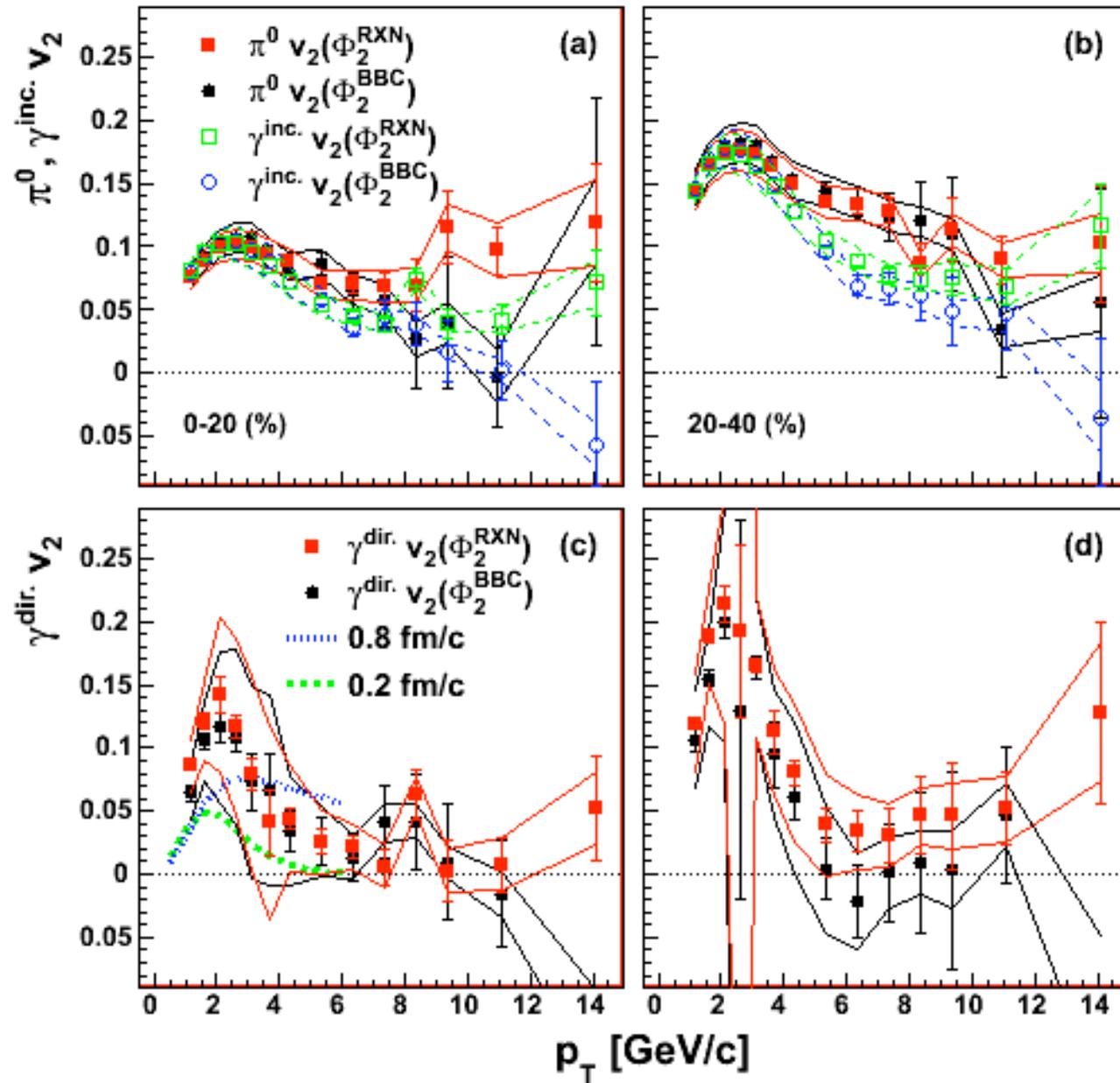
200GeV Au+Au (min. bias)

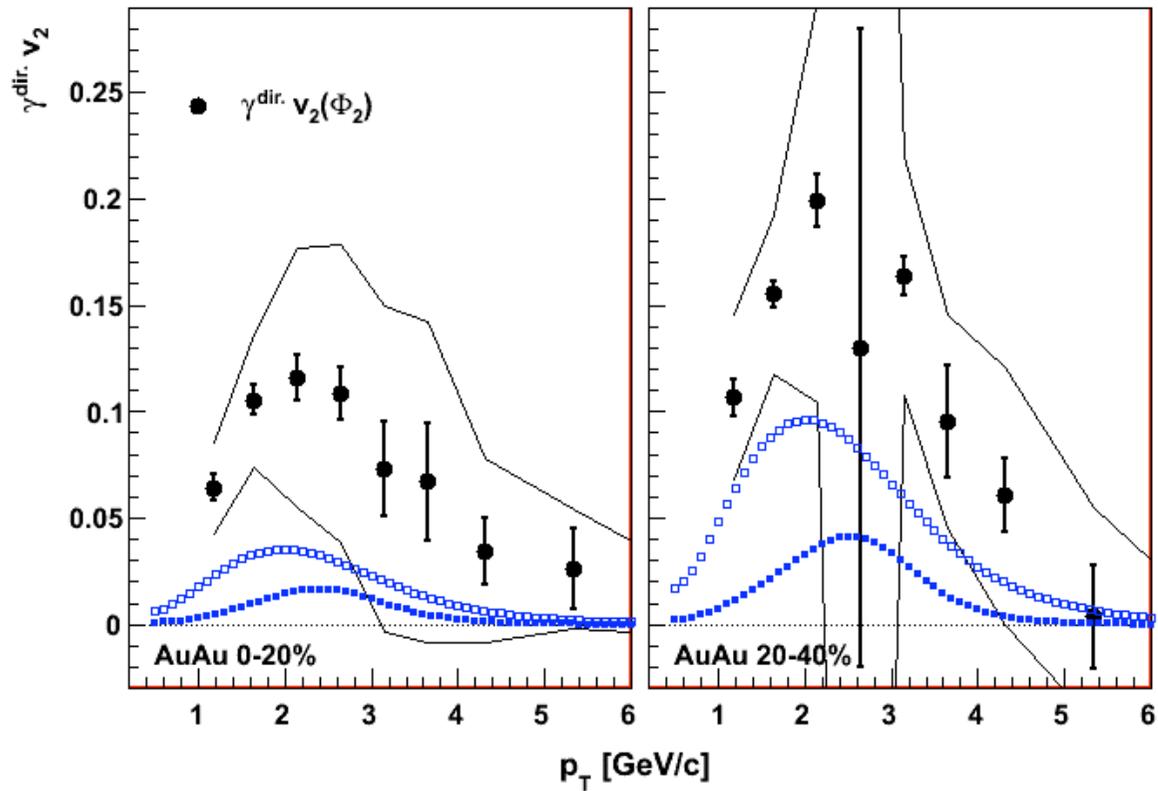
arXiv:1105.NNNN



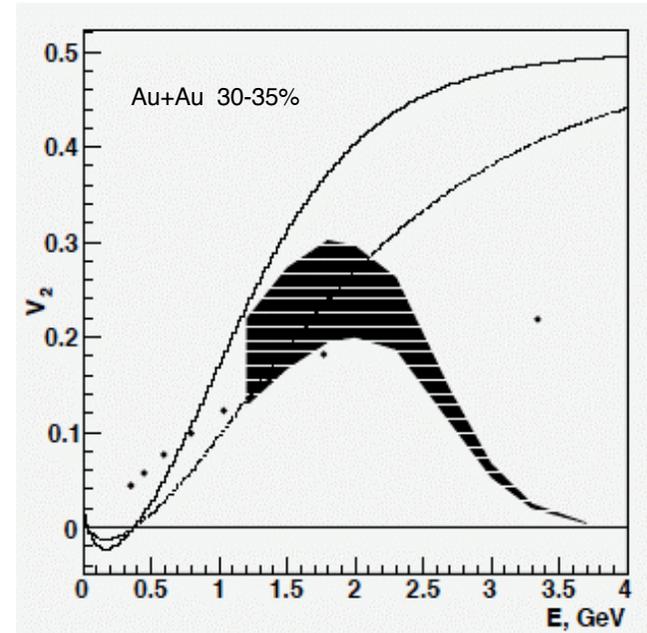
similar to hadron v_2 at low p_T
much smaller v_2 at high p_T







Holopainen, Räsänen, Eskola
arXiv:1104.5371v1



V. S. Pantuev
arXiv:1105.4033v1