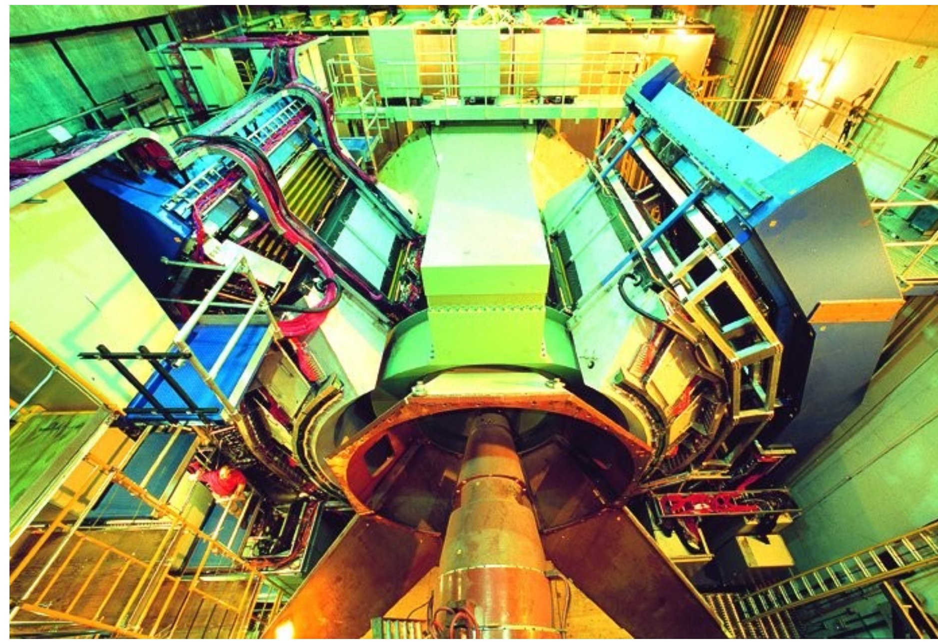
Collective Flow Measurements from the PHENIX Experiment

ShinIchi Esumi for the PHENIX Collaboration



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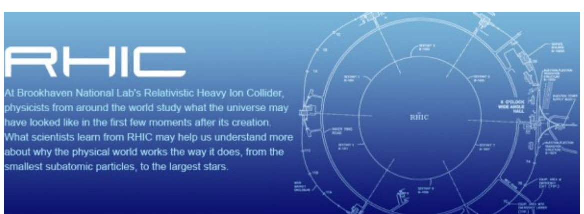
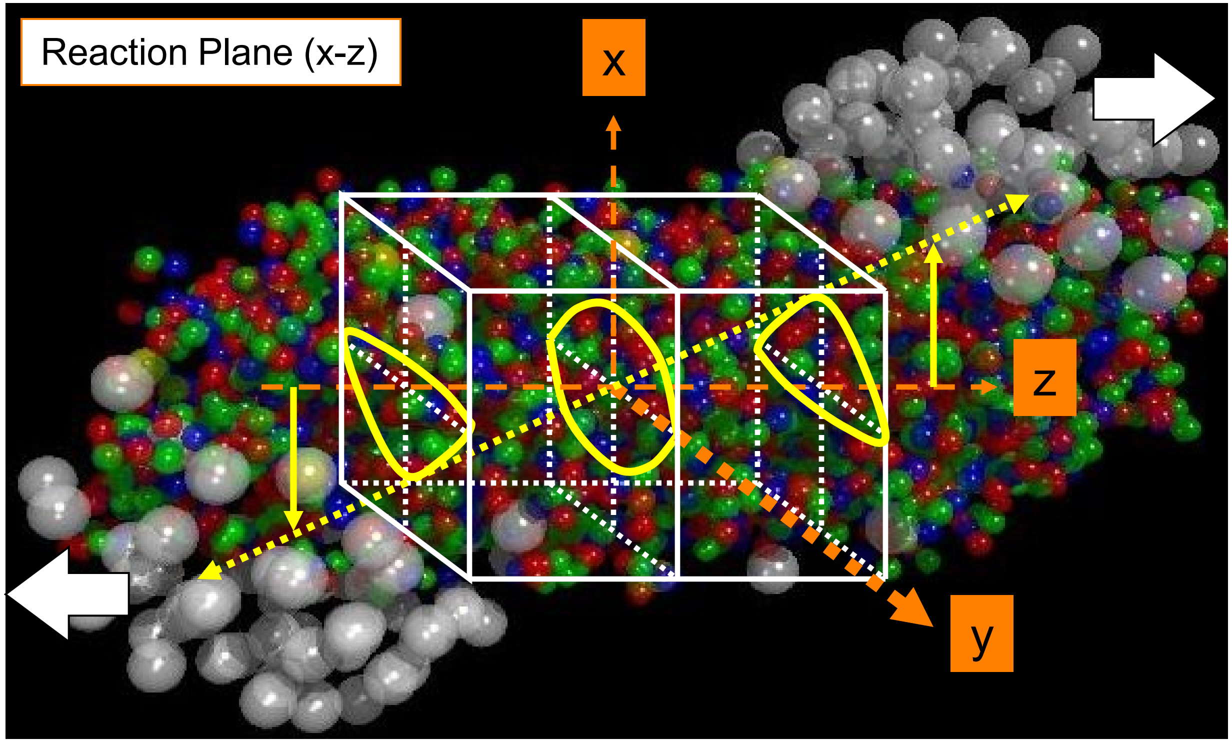
higher order event anisotropy
event plane correlation
v_2,v_3,v_4 in 200GeV Au+Au
2-particle correlation
energy dependence of v_n
direct-photon v_2

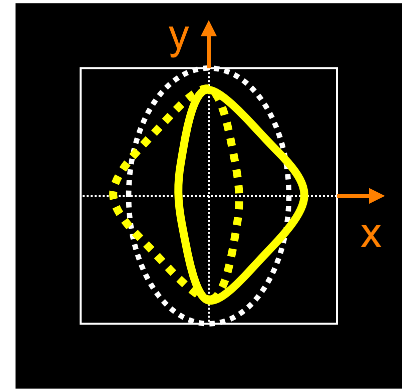


PHENIX

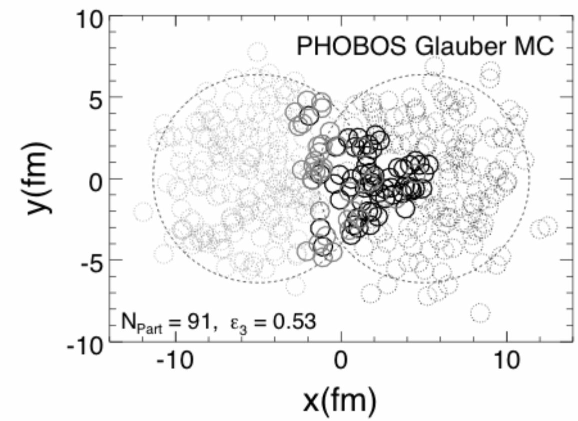
筑波大学 University of Tsukuba

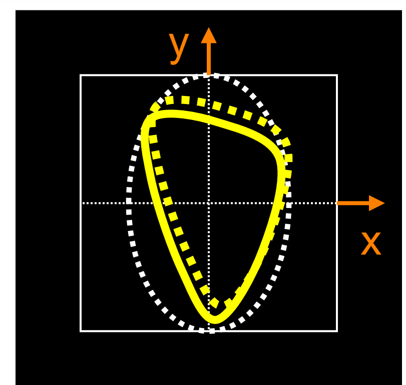
v_3 and Initial Fluctuation





arXiv:1003.0194

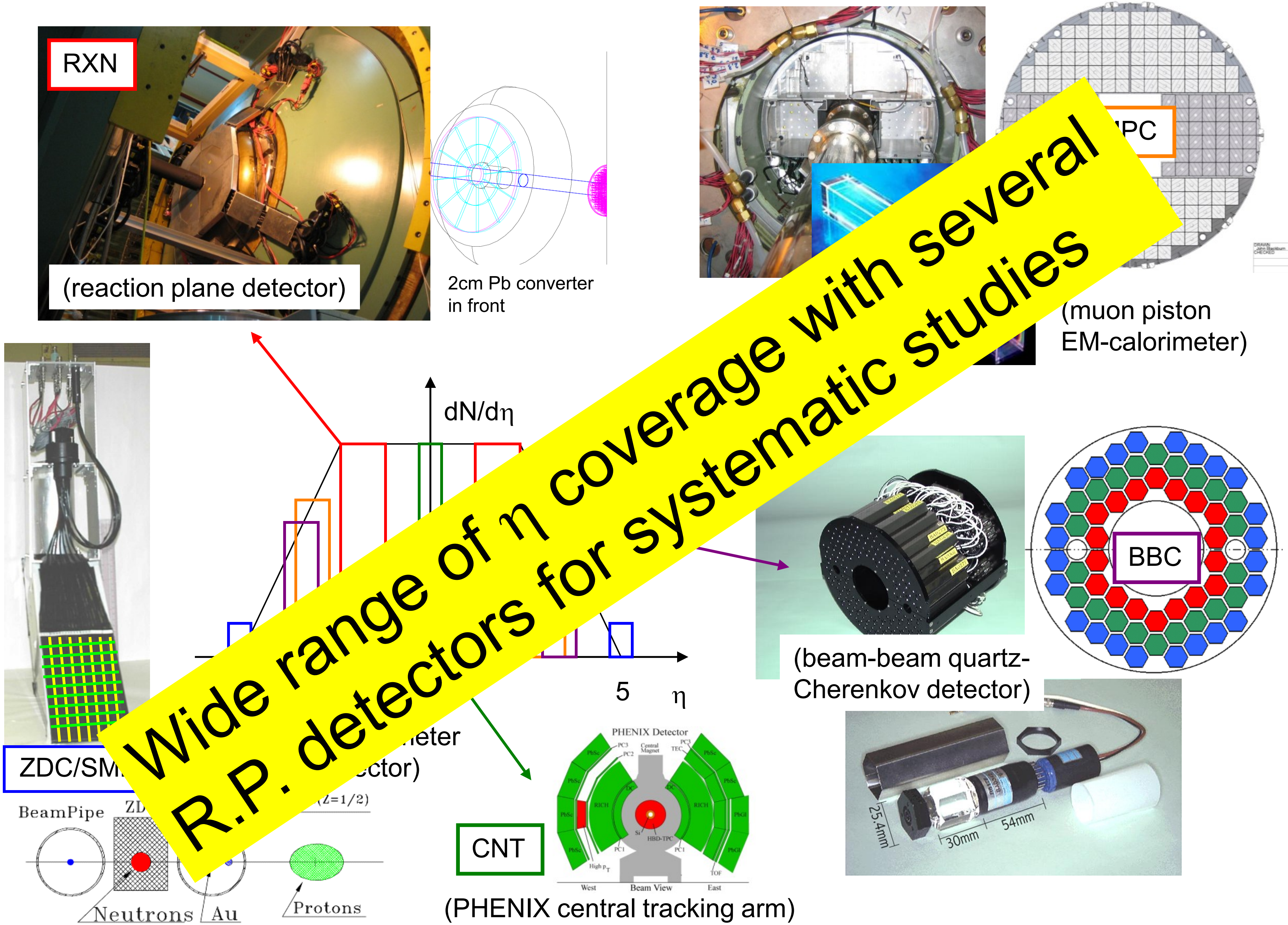




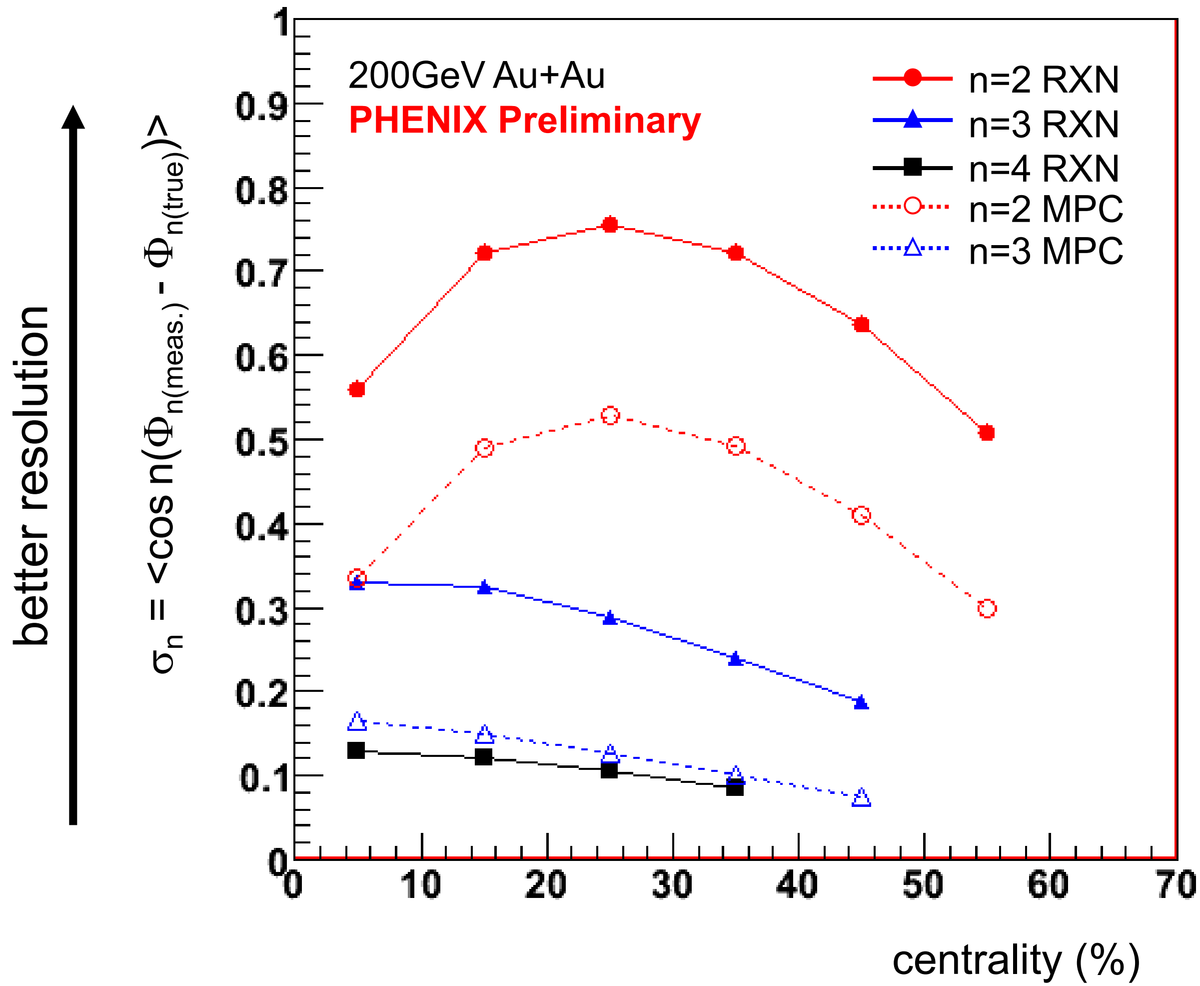
black-disk --> sign-flipping v_3

initial fluctuation --> no-sign-flipping v_3

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



Reaction plane resolution of n^{th} order plane



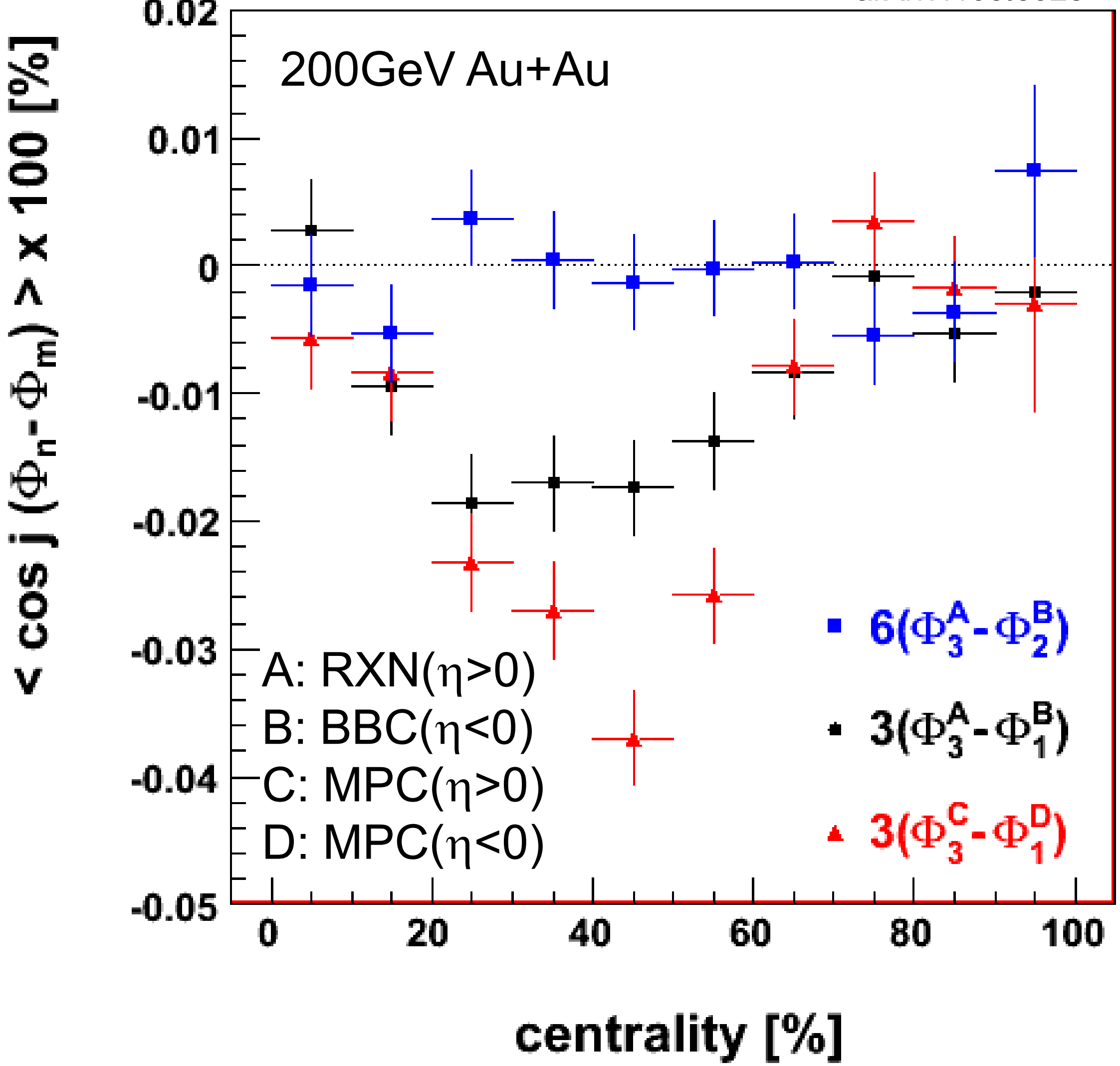
RXN $|\eta|$ = 1.0 ~ 2.8
MPC $|\eta|$ = 3.1~ 3.7

positive correlation in Φ_3 between opposite η up to +/– 3 ~ 4

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

No visible correlation between Φ_3 and Φ_2

arXiv:1105.3928

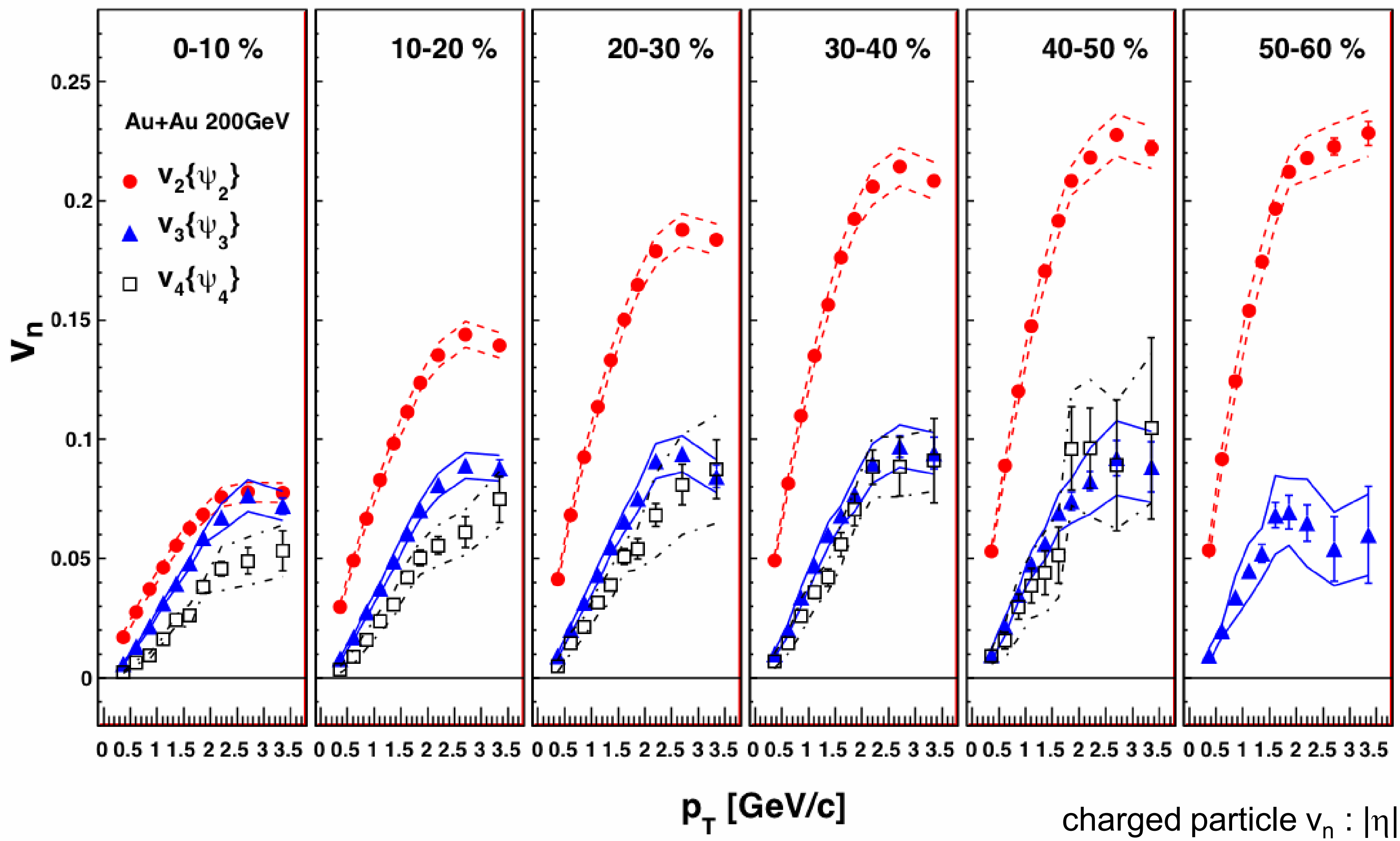


- same harmonics
  $2(\Phi_2-\Phi_2)$ ~ 10%
  $3(\Phi_3-\Phi_3)$ ~ 1%
- weak negative correlation between Φ_3 and Φ_1
- hint for rapidity anti-symmetric v_3 contribution

Fluctuation dominance for Φ_3

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

arXiv:1105.3928



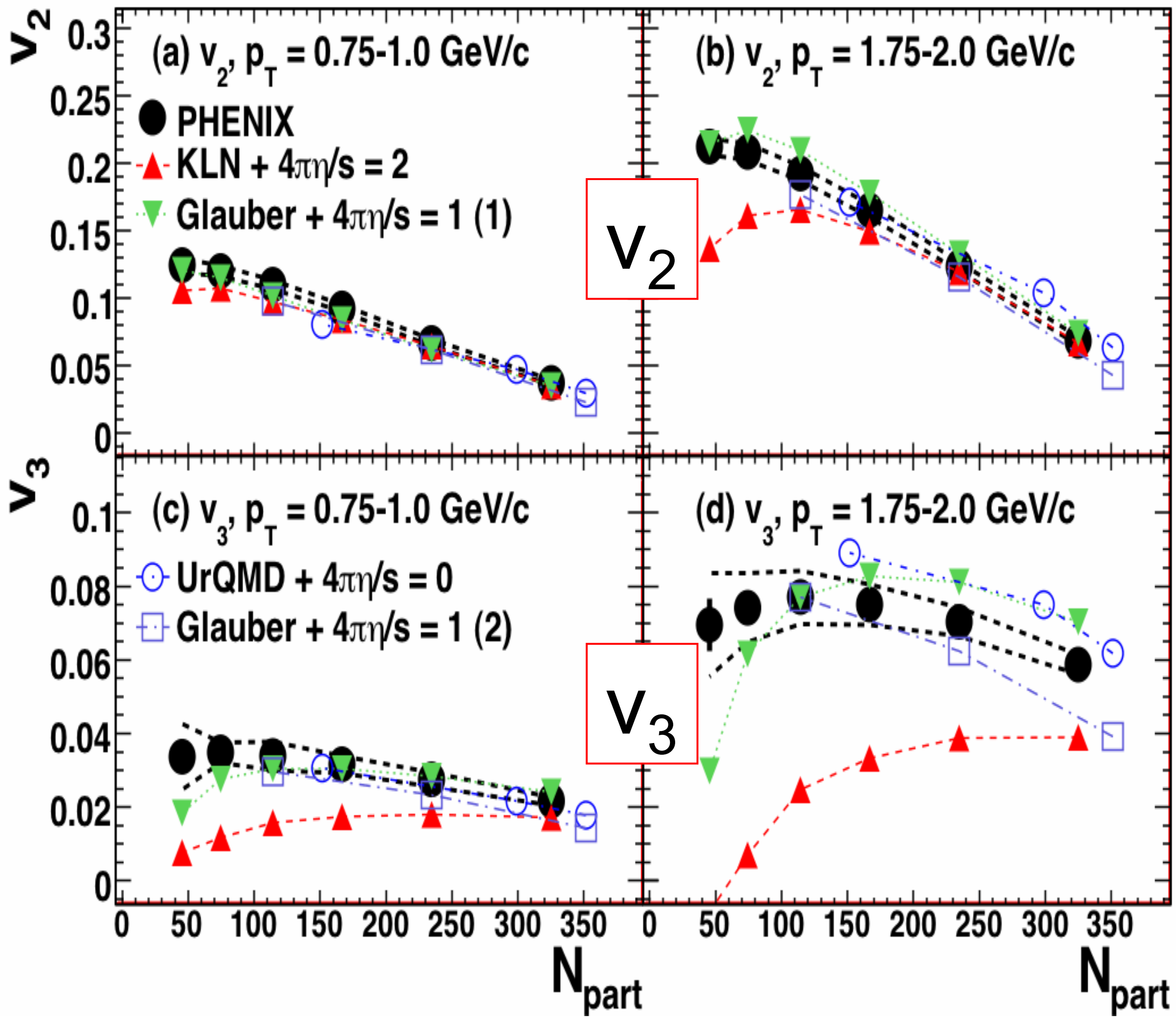
charged particle v_n : $|\eta|<0.35$
reaction plane Φ_n : $|\eta|=1.0\sim2.8$

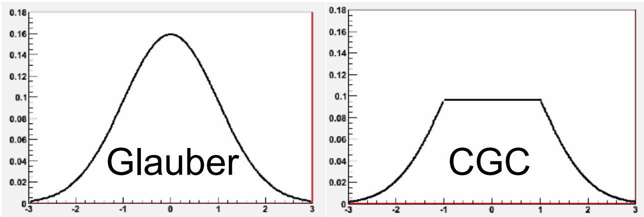
(1) v_3 is comparable to v_2 at 0~10%
(2) weak centrality dependence on v_3
(3) $v_4\{\Phi_4\} \sim 2 \times v_4\{\Phi_2\}$

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.

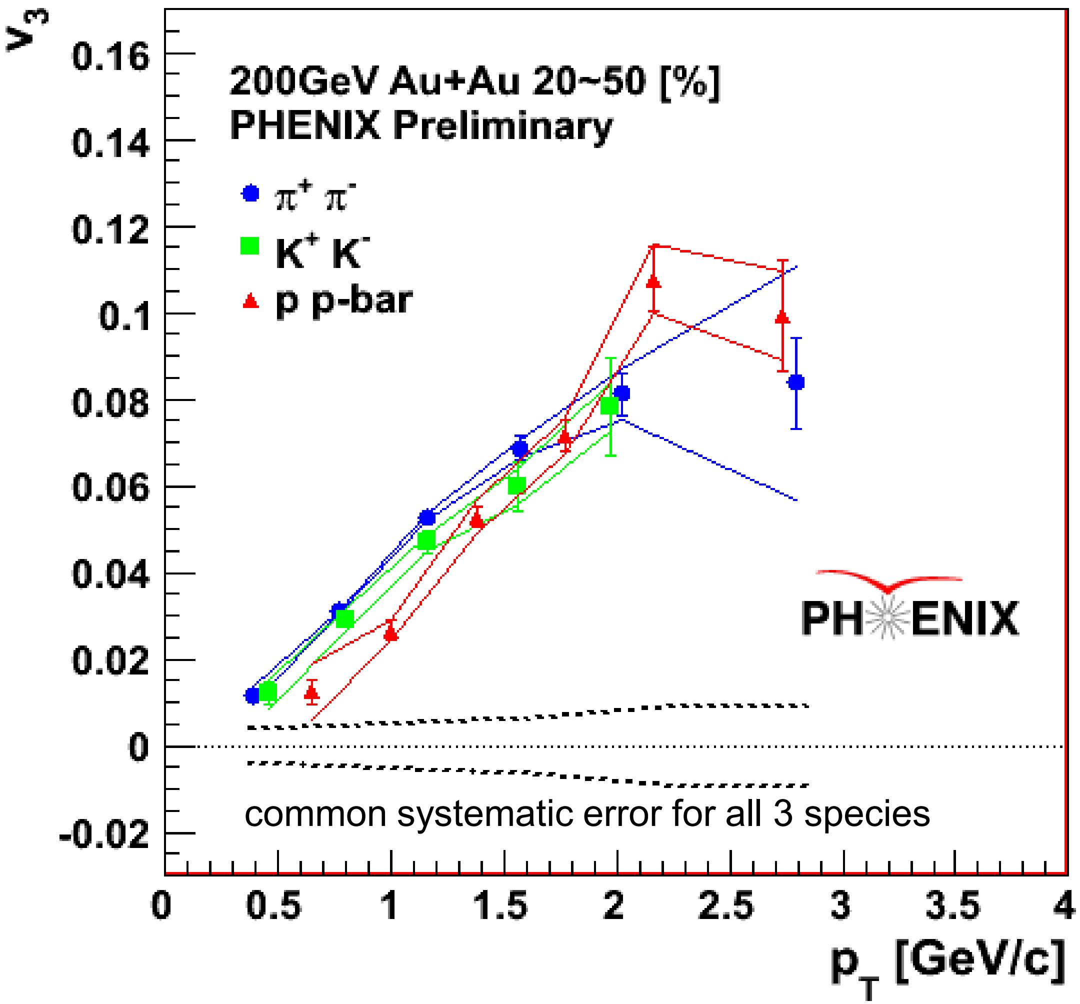
Glauber & $4\pi\eta/s=1$ *works*

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

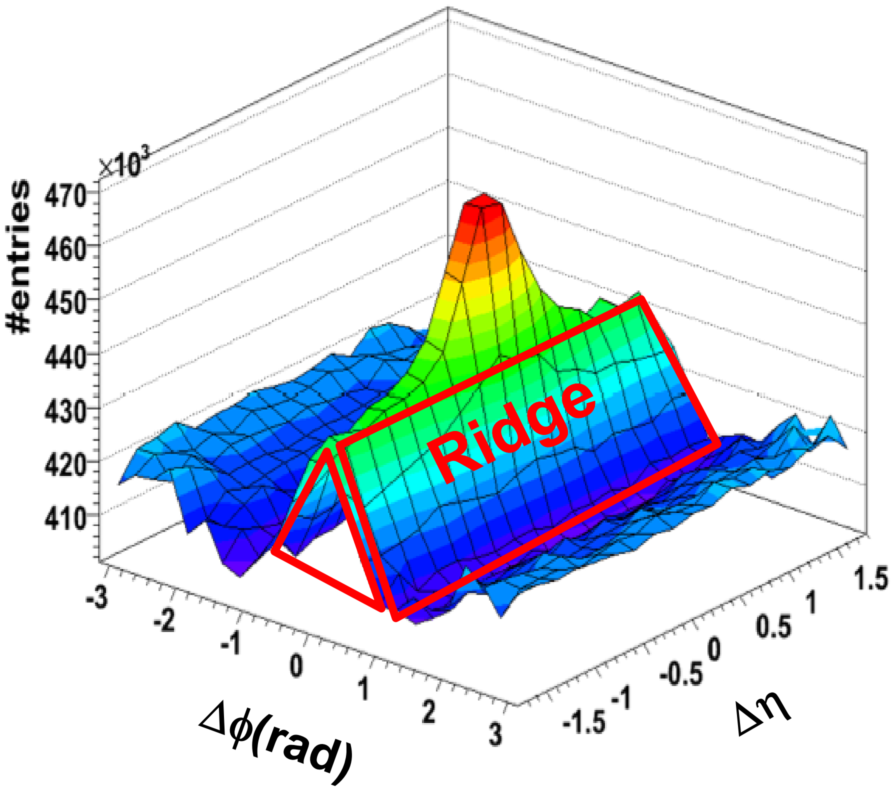


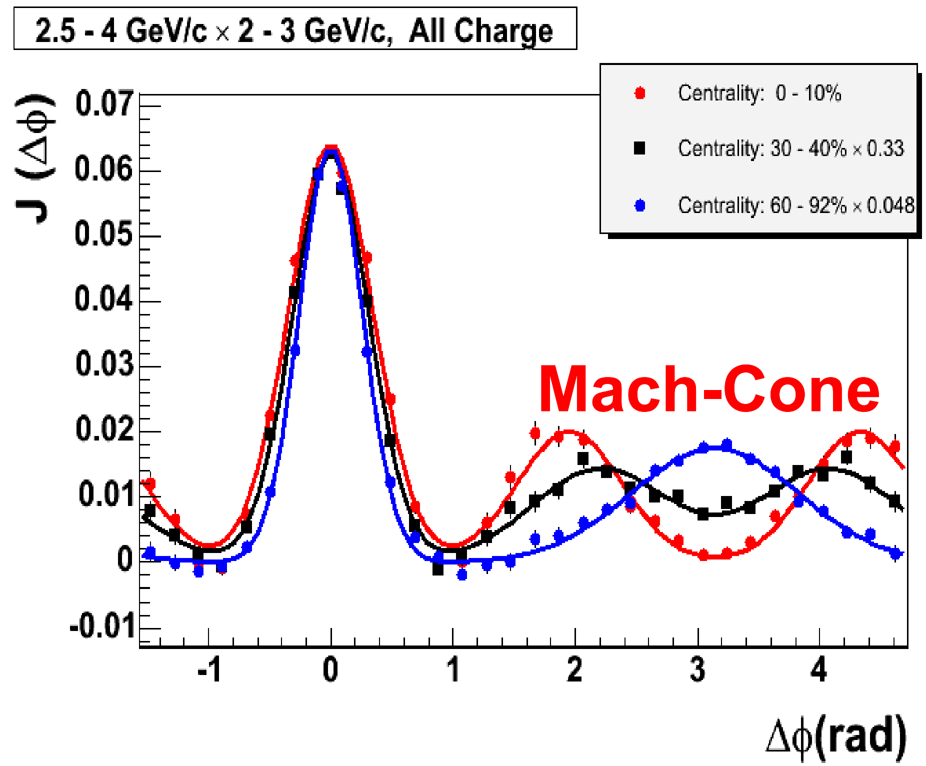
- lower p_T
  particle mass dependence
  radial flow

- 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?



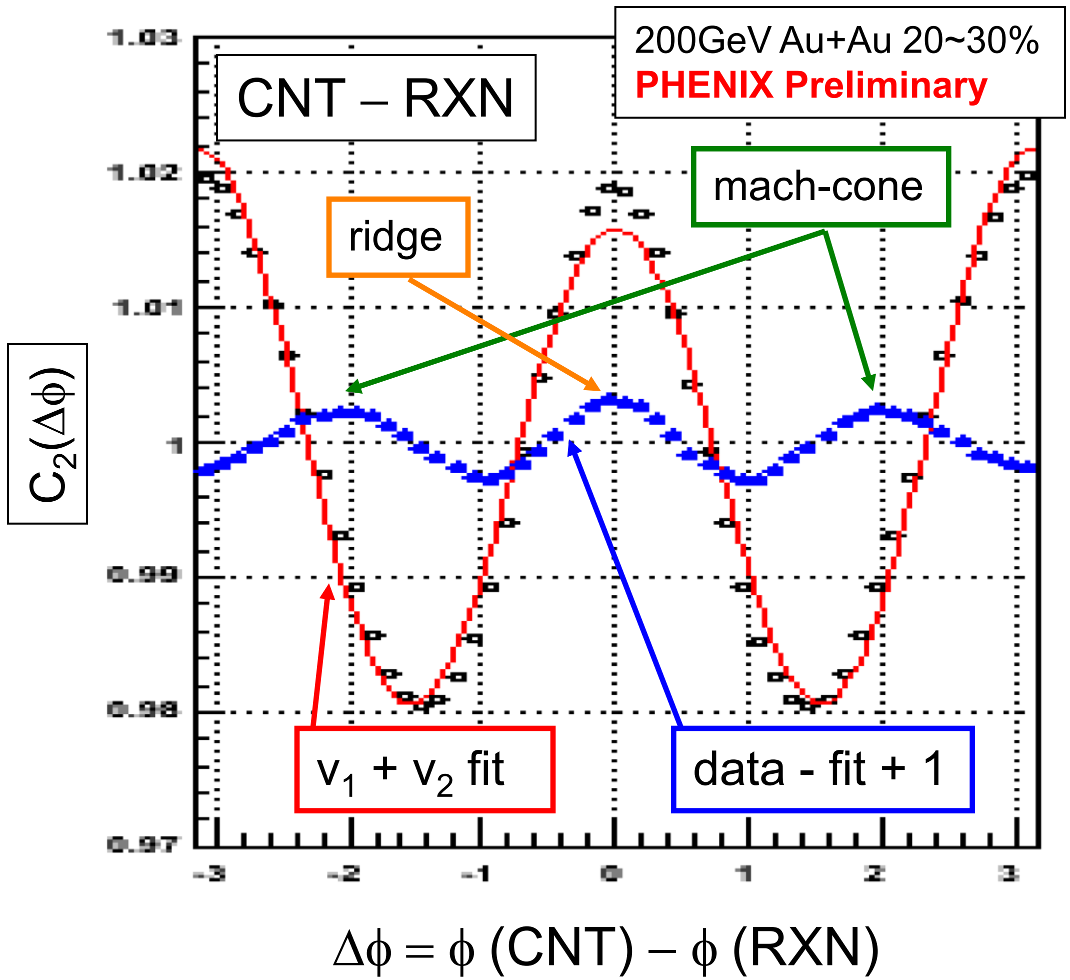


Ridge : long range $\Delta\eta$ correlation at near-side

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

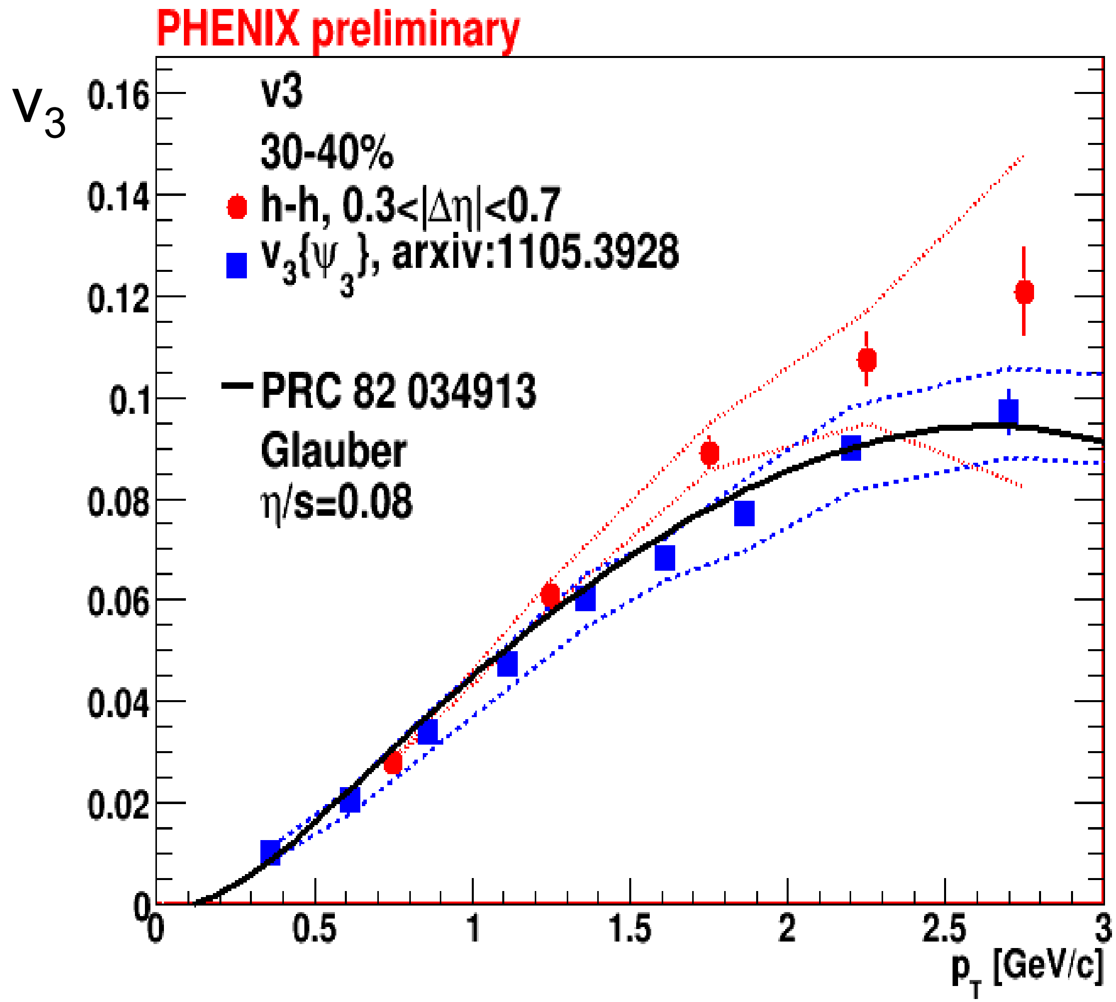


RXN: $|\eta|$=1.0~2.8
CNT: ($|\eta|$<0.35)
charged hadrons
p_T=2~4(GeV/c)

clear 3[rd] 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.)

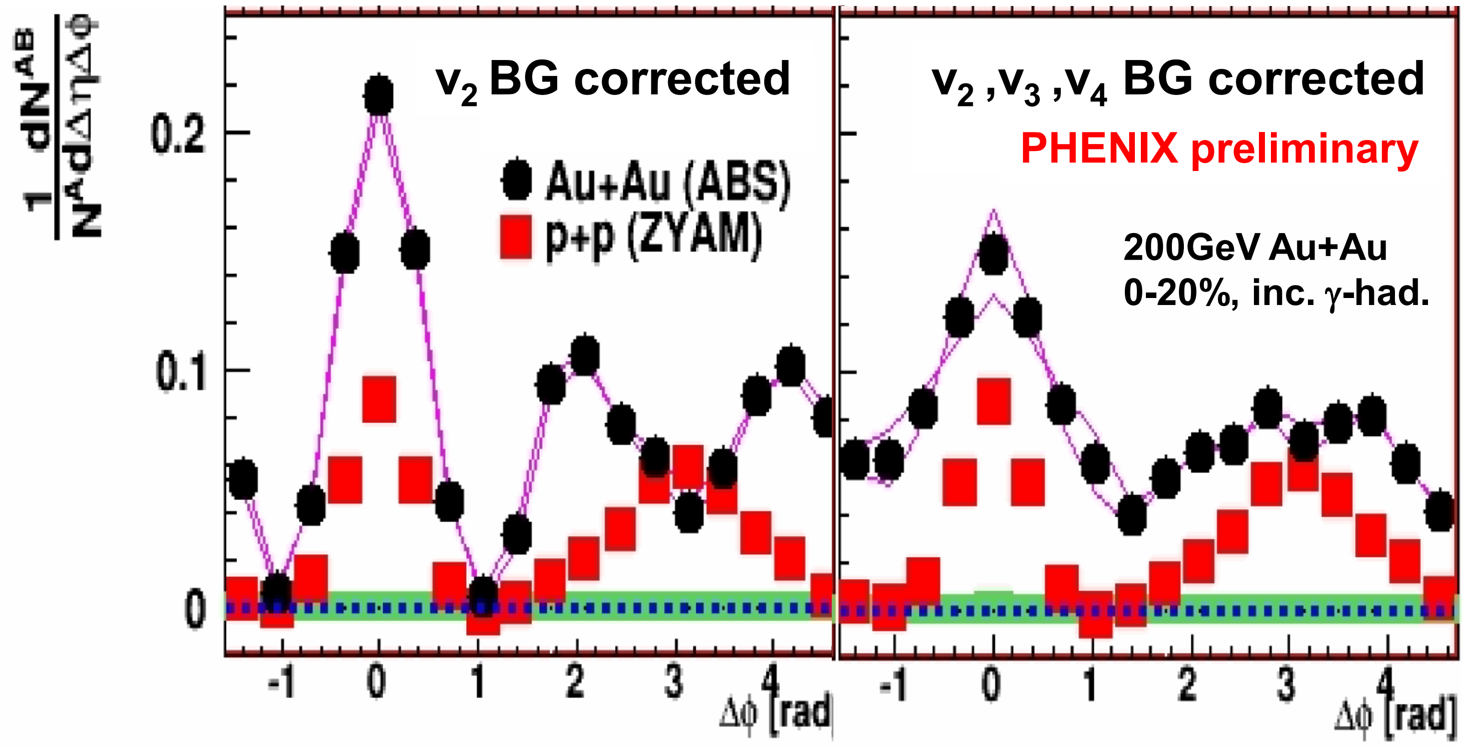
small difference

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)

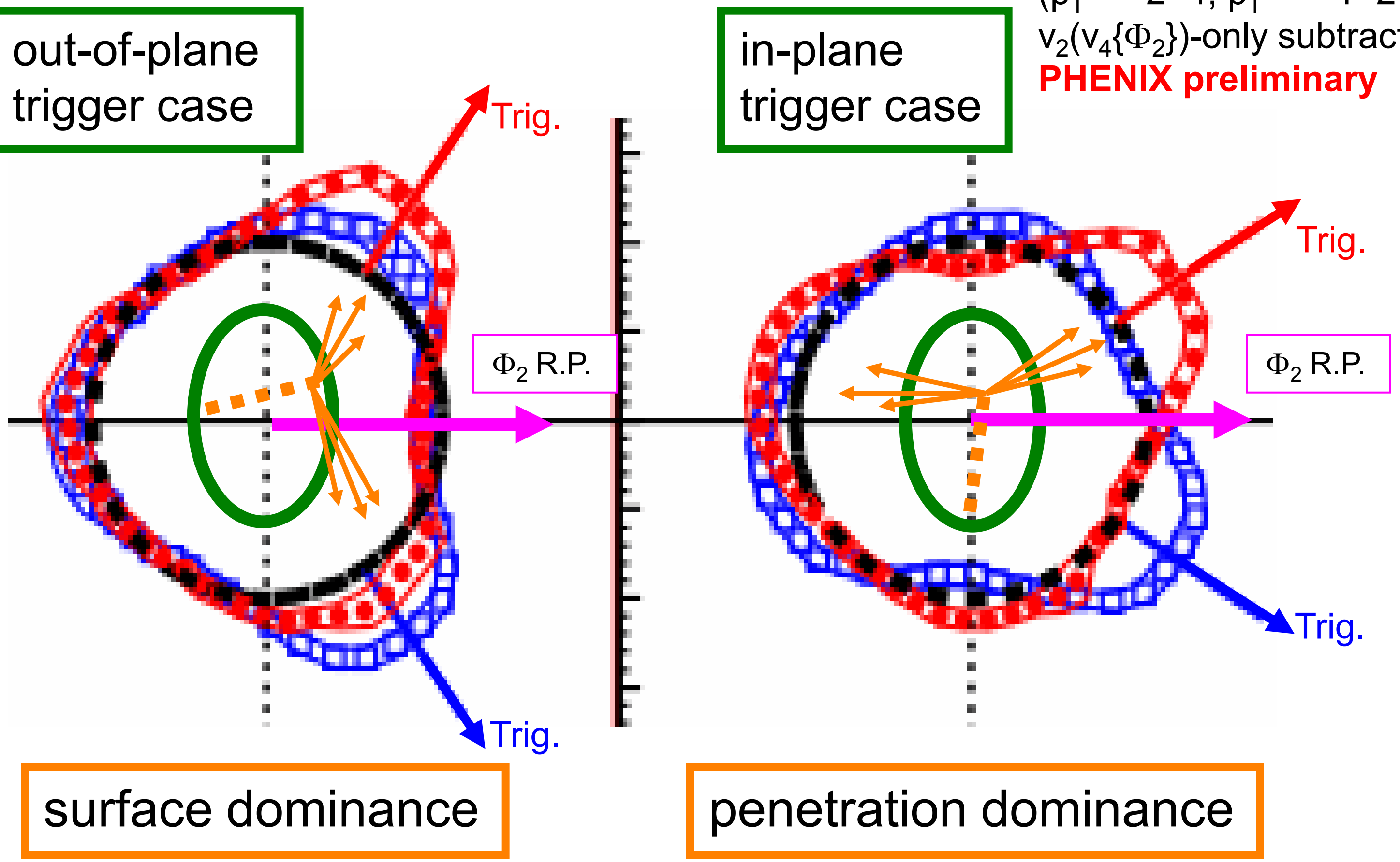
Observed left/right asymmetry remains after "the usual/normal" v_3 subtraction.

200GeV Au+Au -> h-h
(p_T^{Trig}=2~4, p_T^{Asso}=1~2GeV/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)

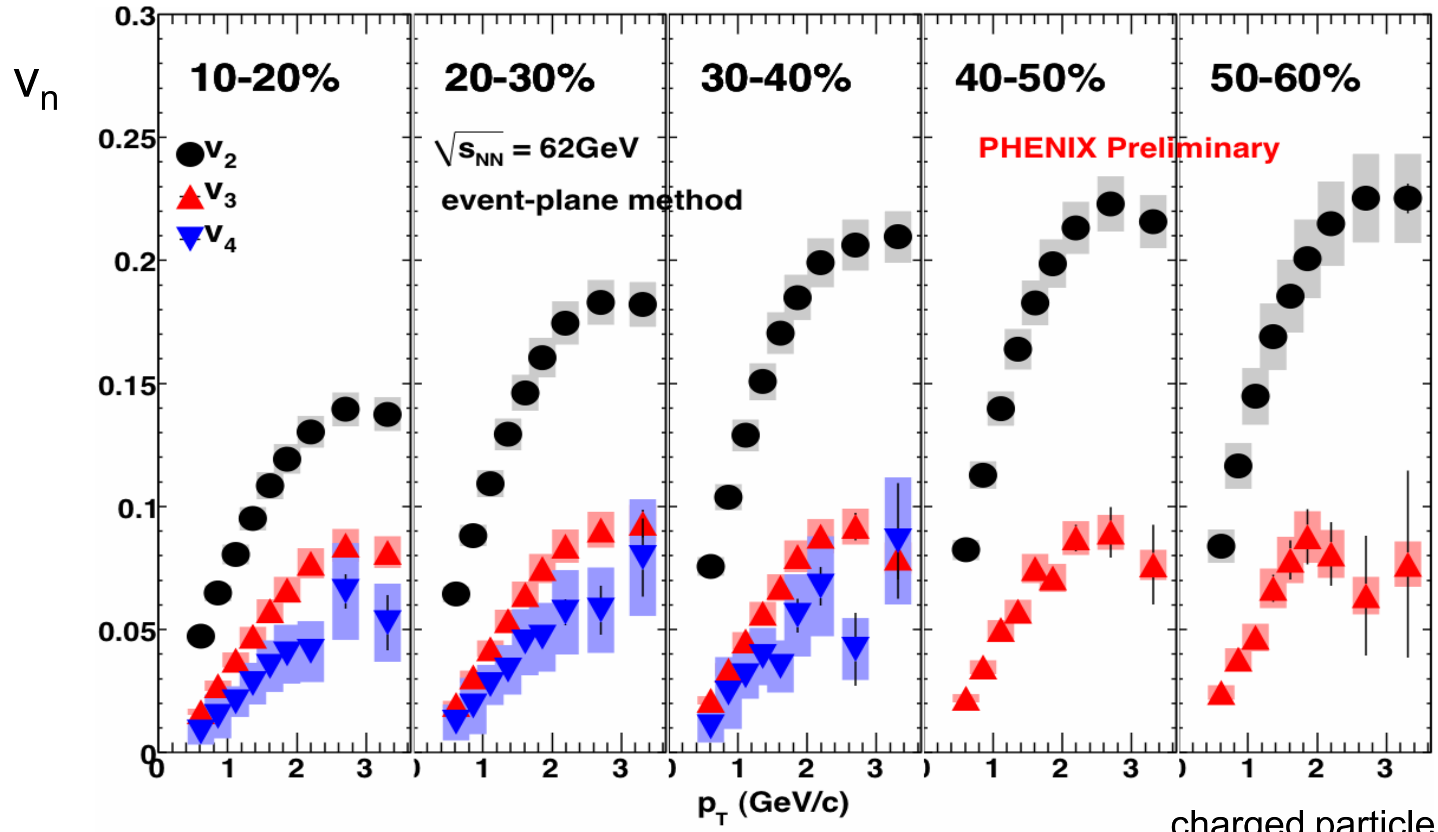
Trigger angle selected 2-part. corr. data are plotted in polar coordinate by rotating Φ_2 R.P. angle as X-axis.

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

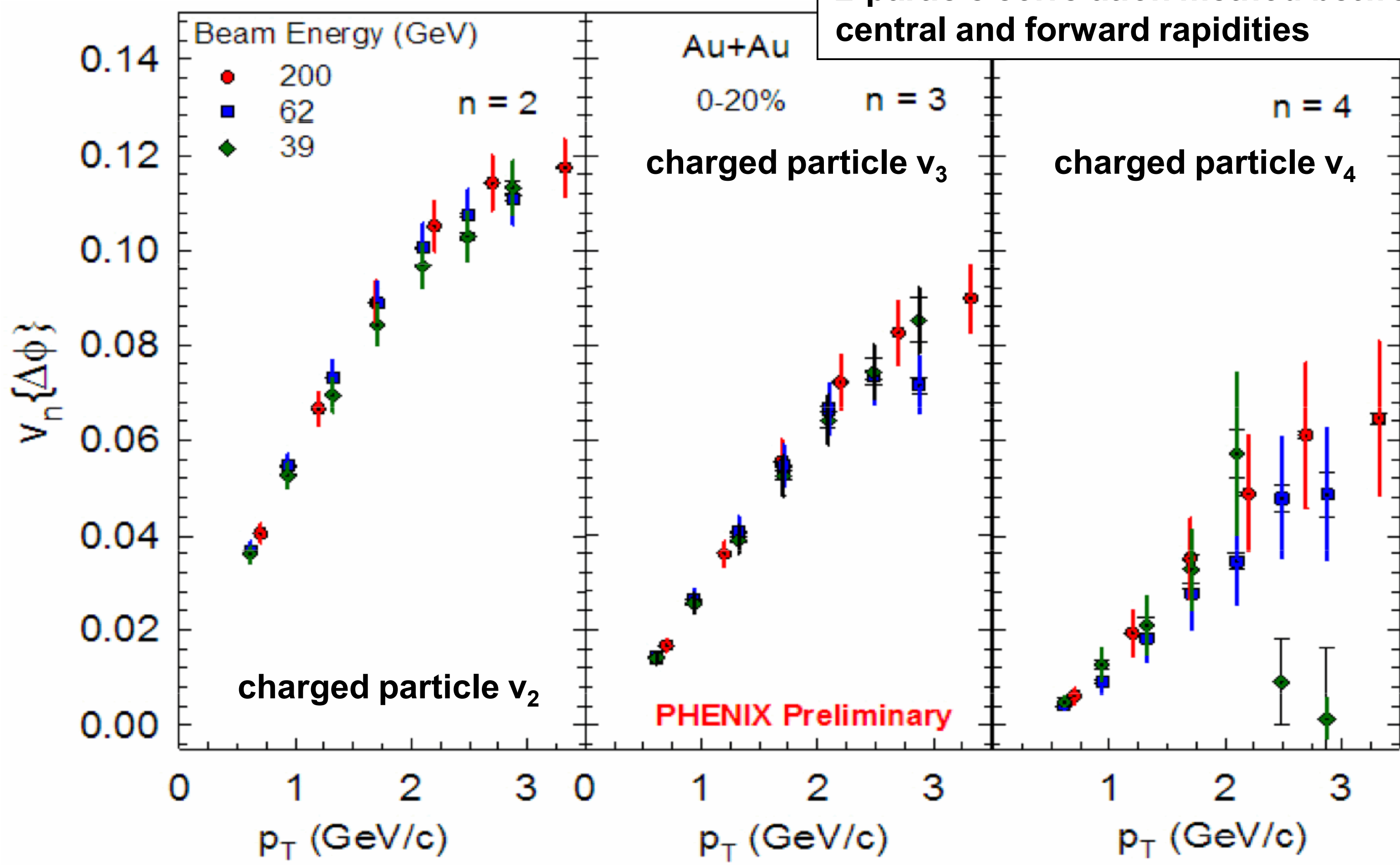


charged particle v_n : $|\eta|<0.35$
reaction plane Φ_n : $|\eta|=1.0\sim2.8$

similar results down to Au+Au 39GeV

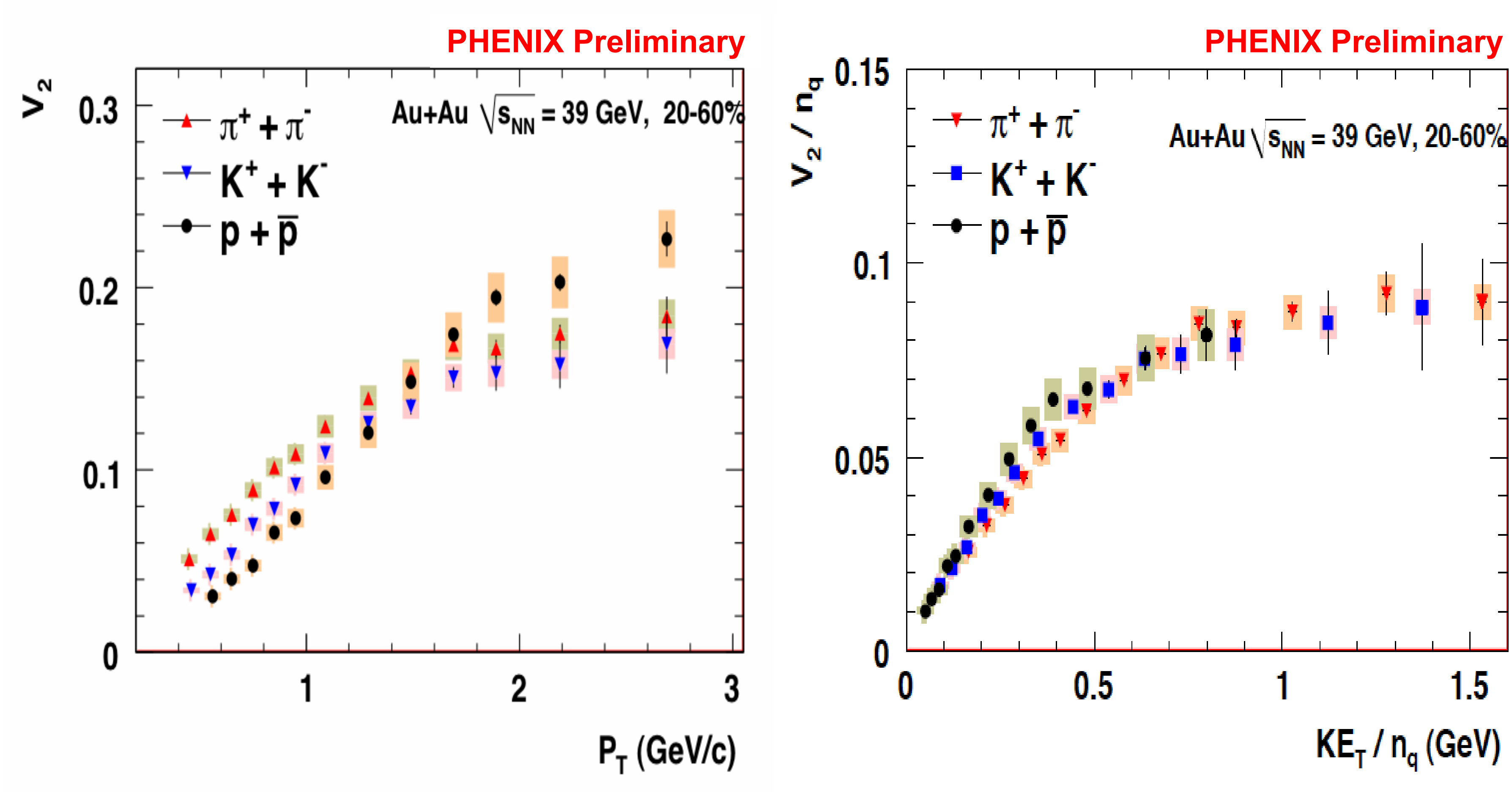
Beam energy dependence 39/62/200GeV Au+Au

2-particle correlation method between central and forward rapidities



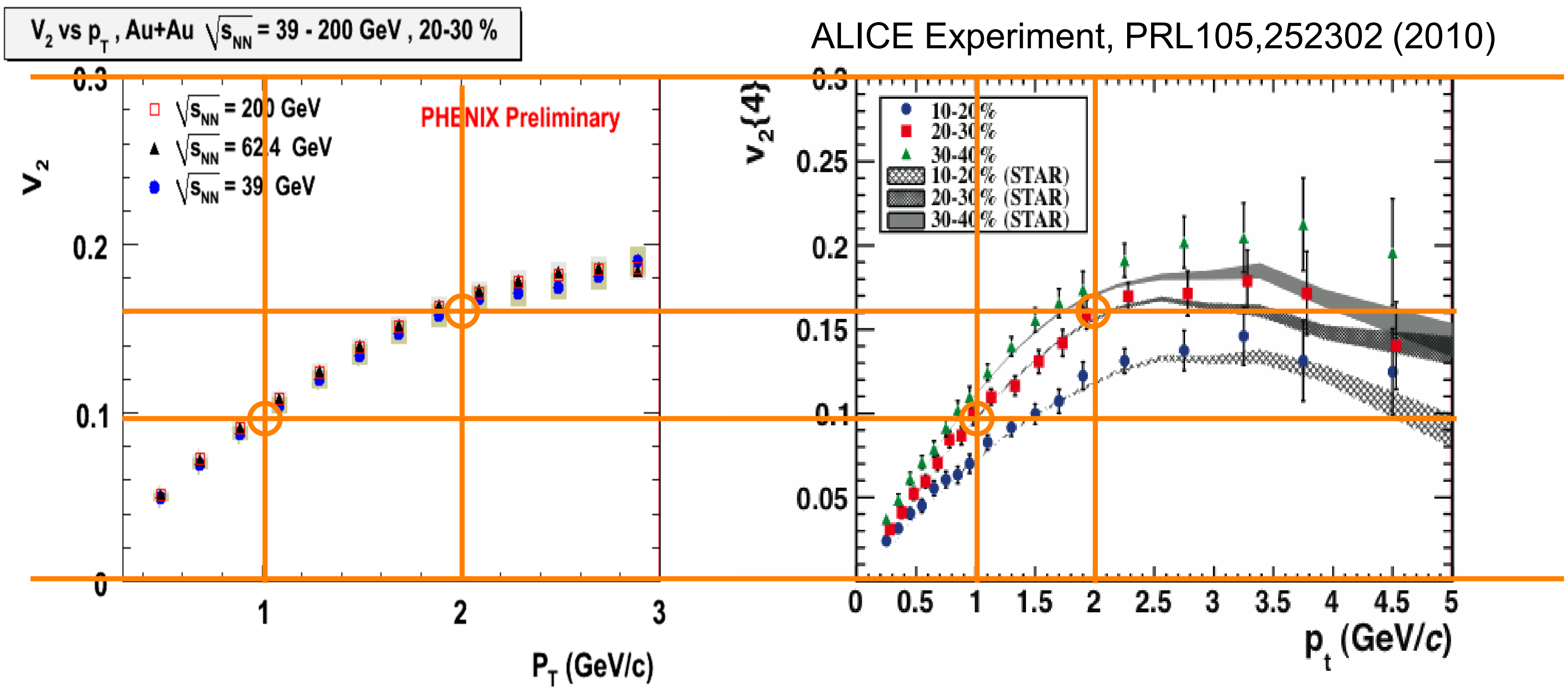
similar hydro-properties down to 39GeV

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



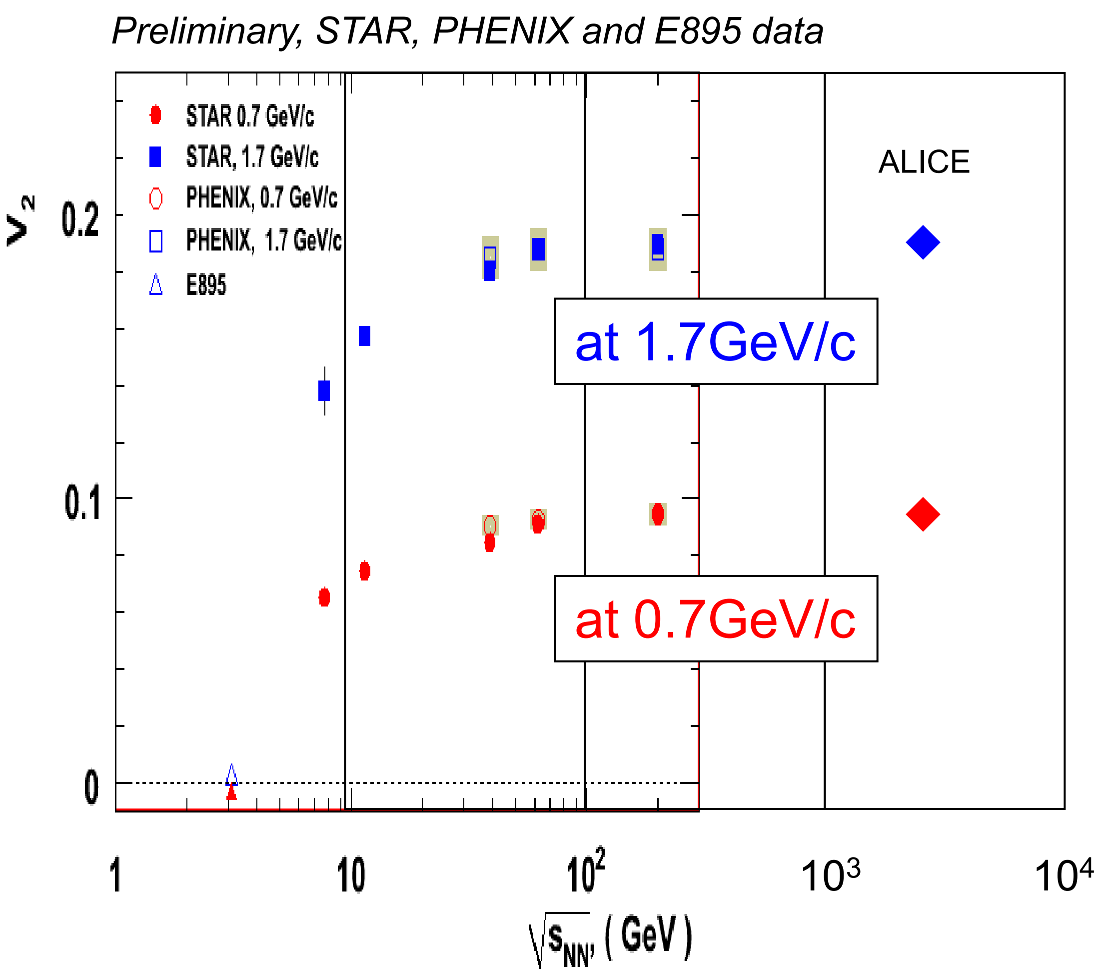
Partonic collective flow down to 39GeV

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



saturation of v_2 for given p_T around or below 39GeV

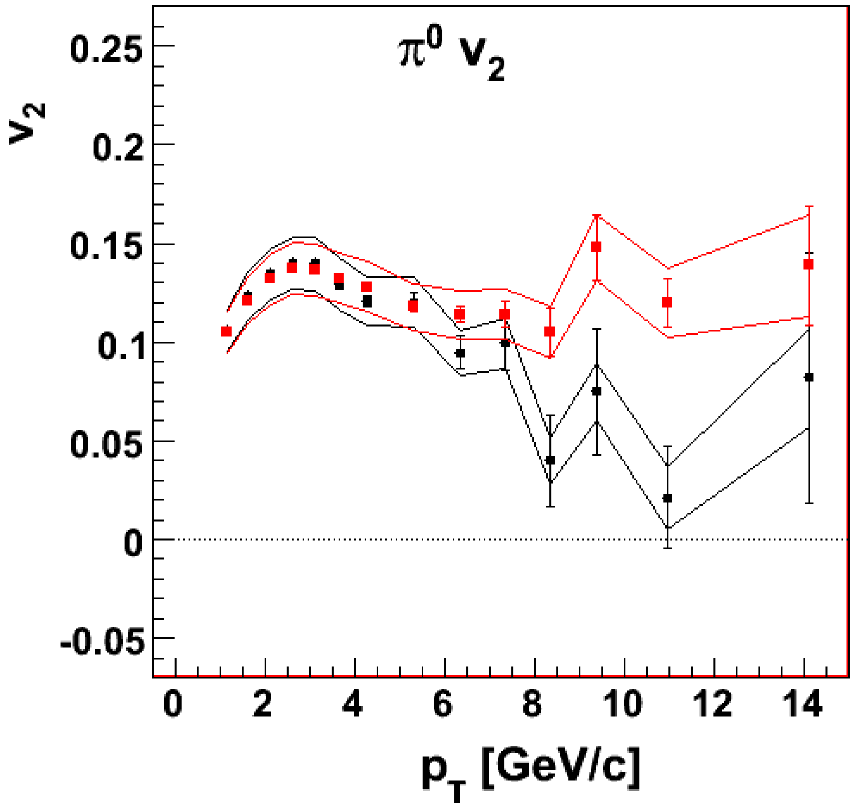
$<v_2>$ still increases mainly because of the $<p_T>$ rise.

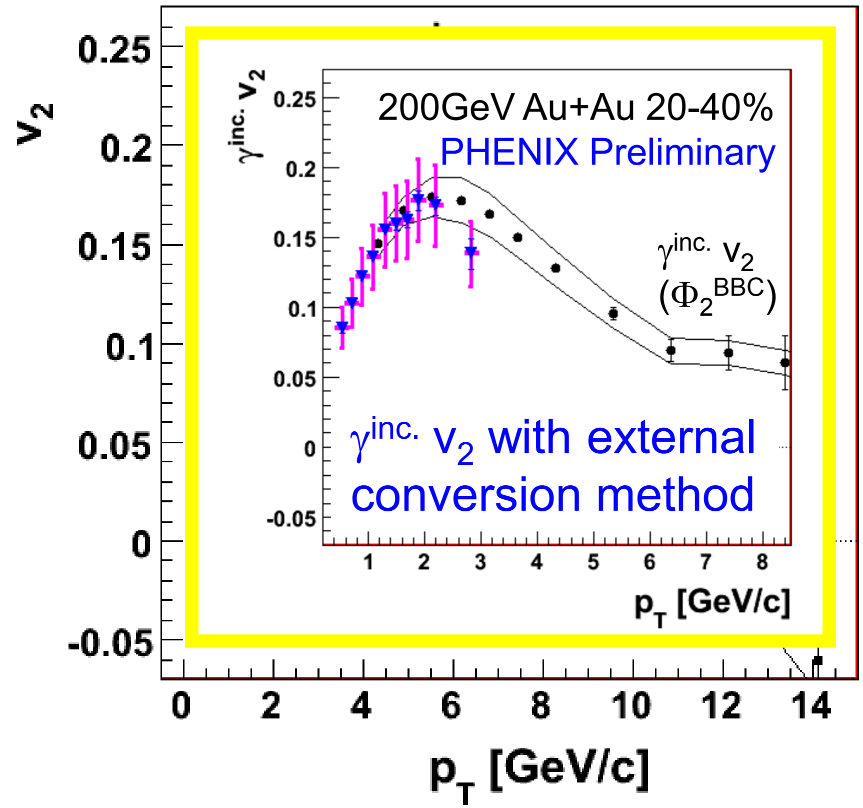
Almost perfect fluidity from 39GeV to 2.76TeV

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

200GeV Au+Au (min. bias)

arXiv:1105.4126

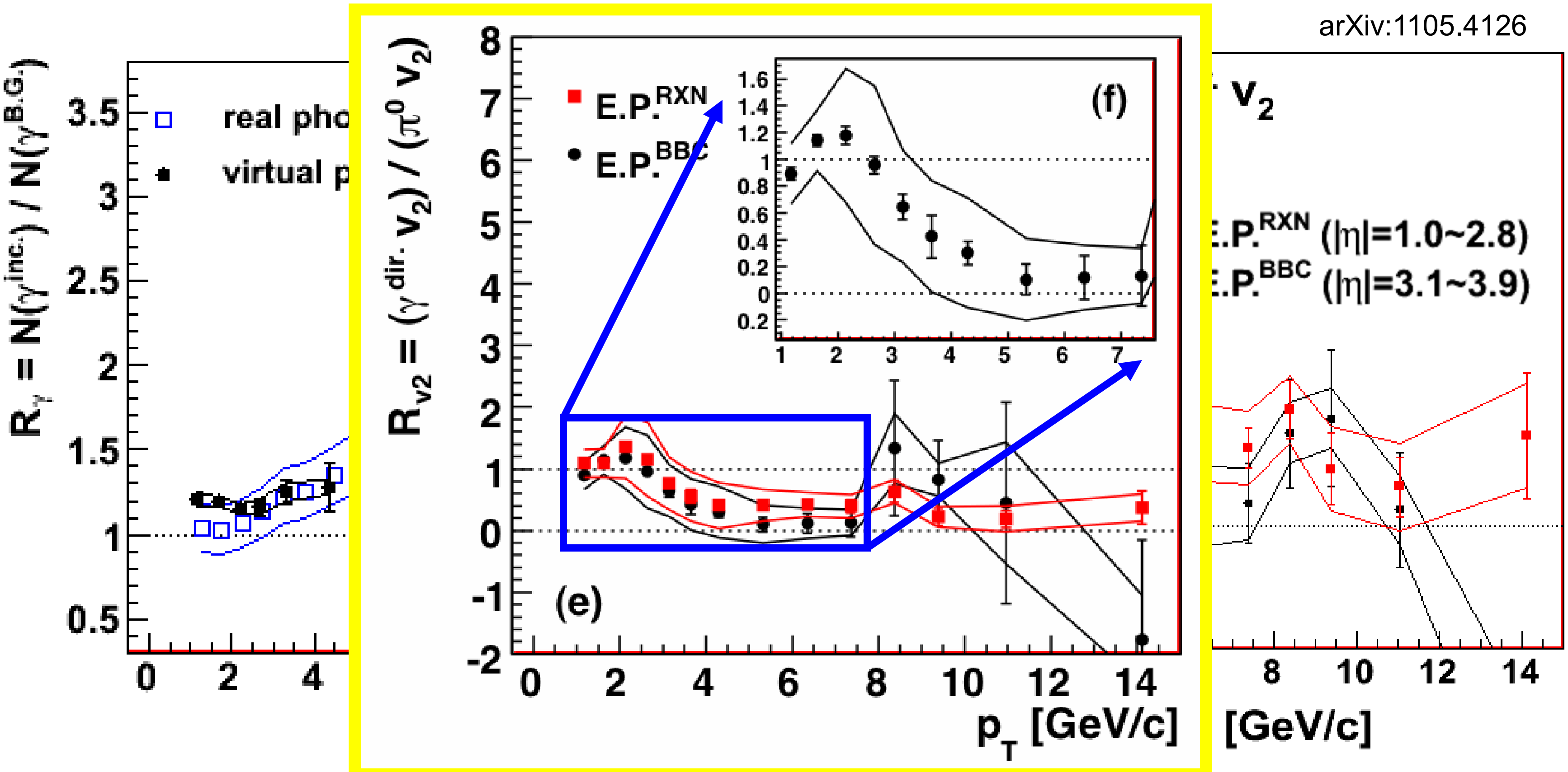




significant difference between π^0 and $\gamma^{inc.}$ v_2 above 5GeV/c, difference between $v_2^{\{RXN\}}$ and $v_2^{\{BBC\}}$ due to jet bias.

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

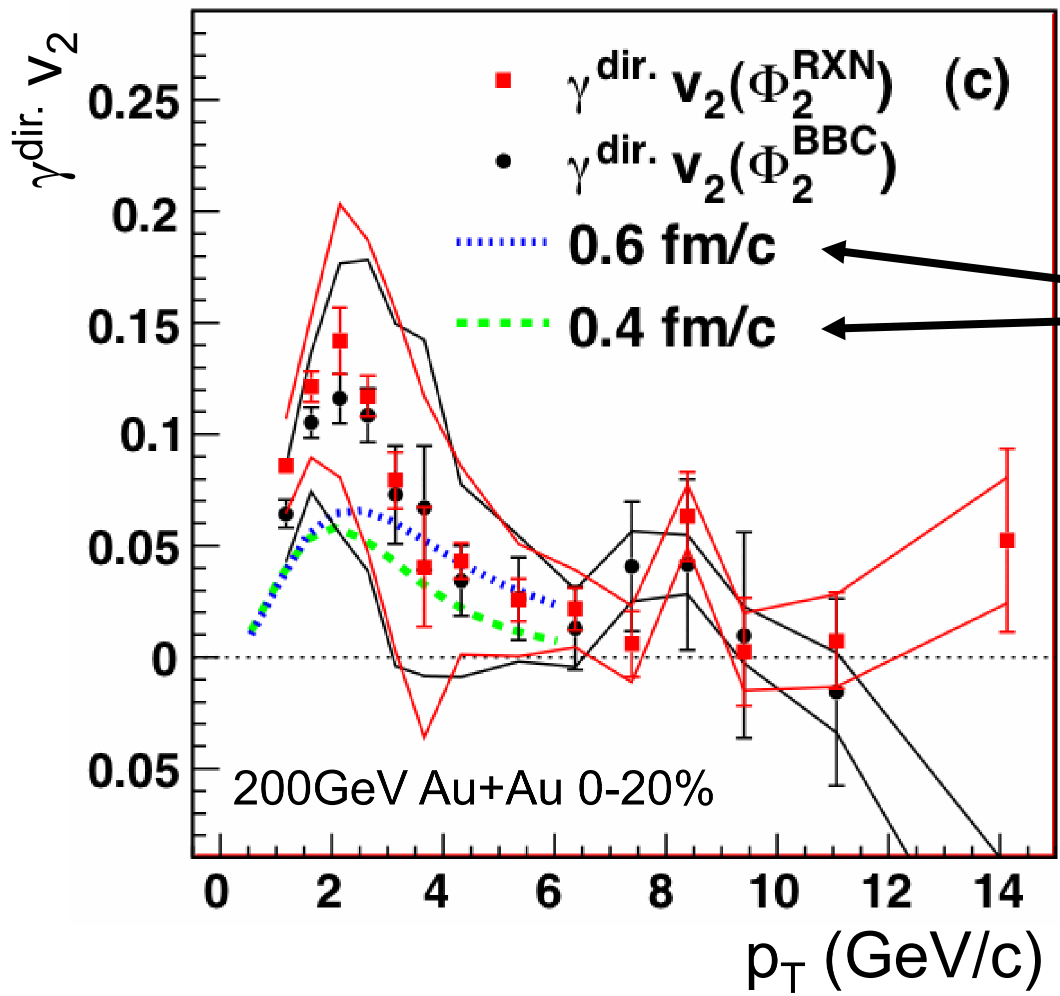
200GeV Au+Au (min. bias)

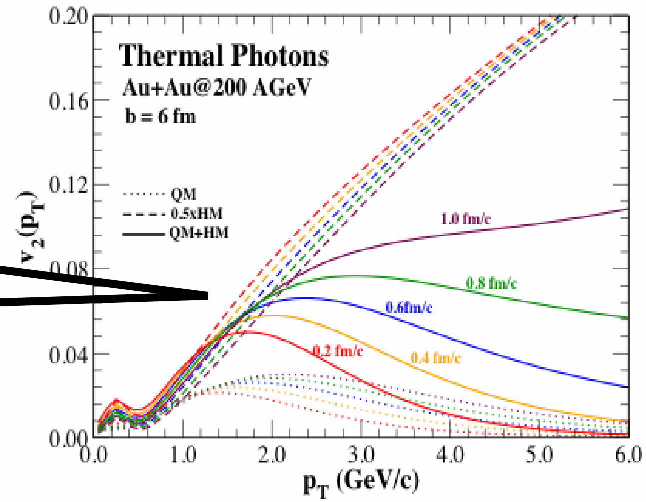


$\gamma^{dir.}$ v_2 is small at high p_T --> consistent with prompt photon

surprisingly large $\gamma^{dir.}$ v_2 seen, similar to hadron v_2 at low p_T.

Comparison of $\gamma^{dir.}$ 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

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 v3 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 collisionswith 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

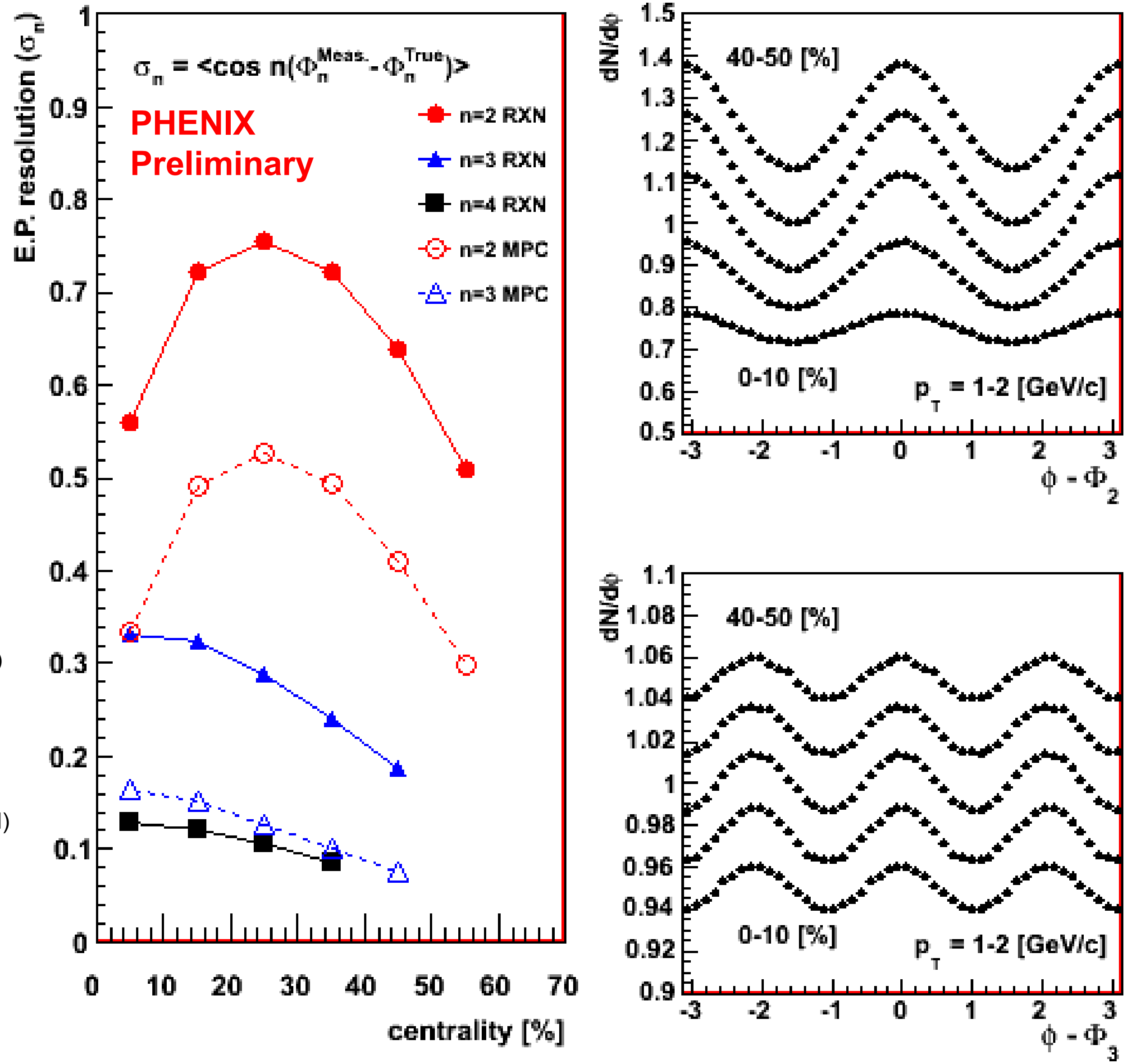
- Significant higher order event anisotropy observed
  - Consistent with initial geometrical fluctuation
  - Break degeneracy: Glauber & $4\pi\eta/s=1$ favored
  - Strong impact on Mach cone and ridge

- 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 $\phi^{track}-\Phi_n^{R.P.}$ distribution



200GeV Au+Au

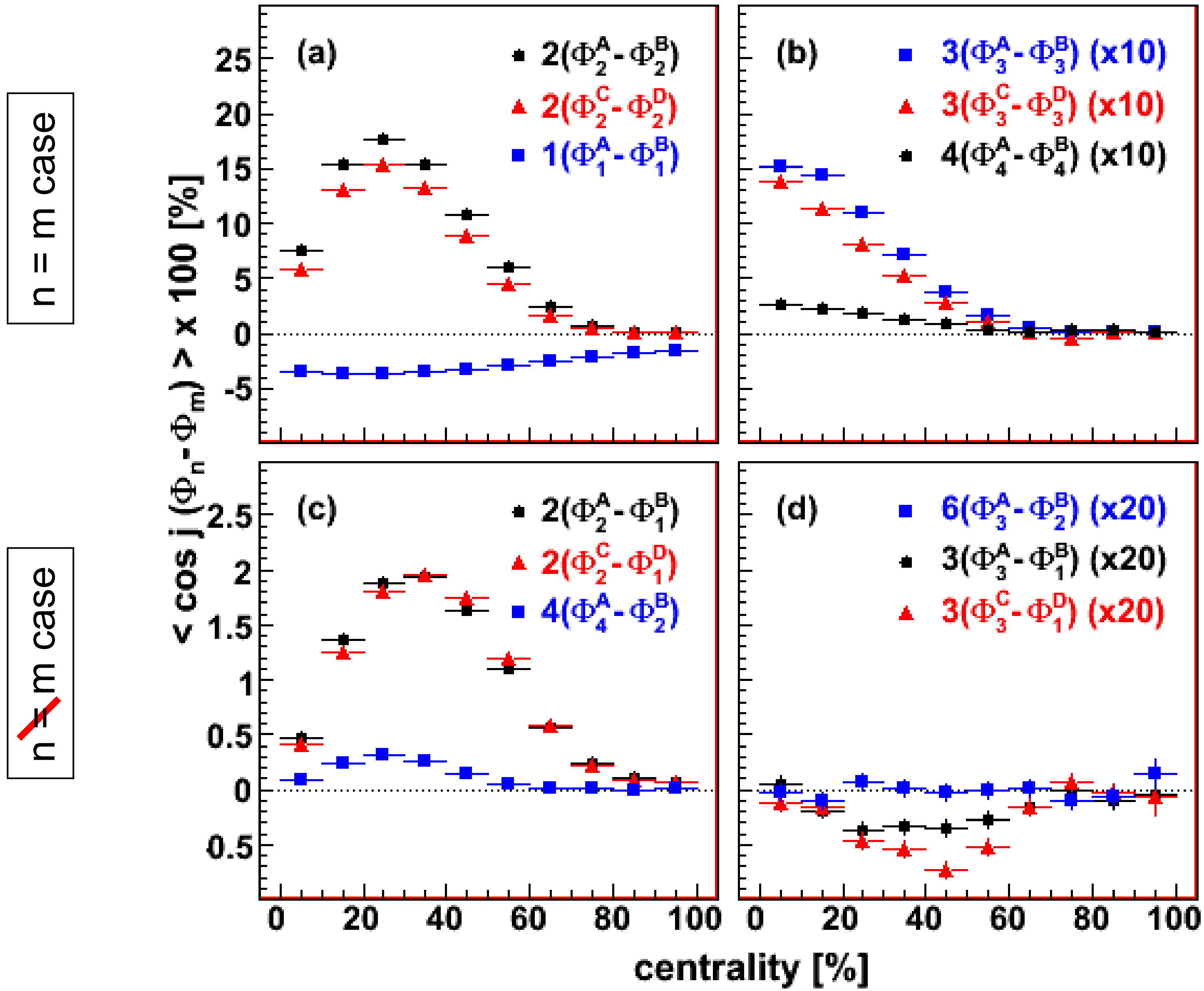
estimated from

$RXN^{(S)} - RXN^{(N)}$
$|\eta| = 1\sim2.8$
$\Delta\eta = 2$

$MPC^{(S)} - MPC^{(N)}$
$|\eta| = 3.1\sim3.7$
$\Delta\eta = 6.2$

Φ_2, Φ_3 and Φ_4 are defined for each event.

Event plane correlation between the same or different harmonics



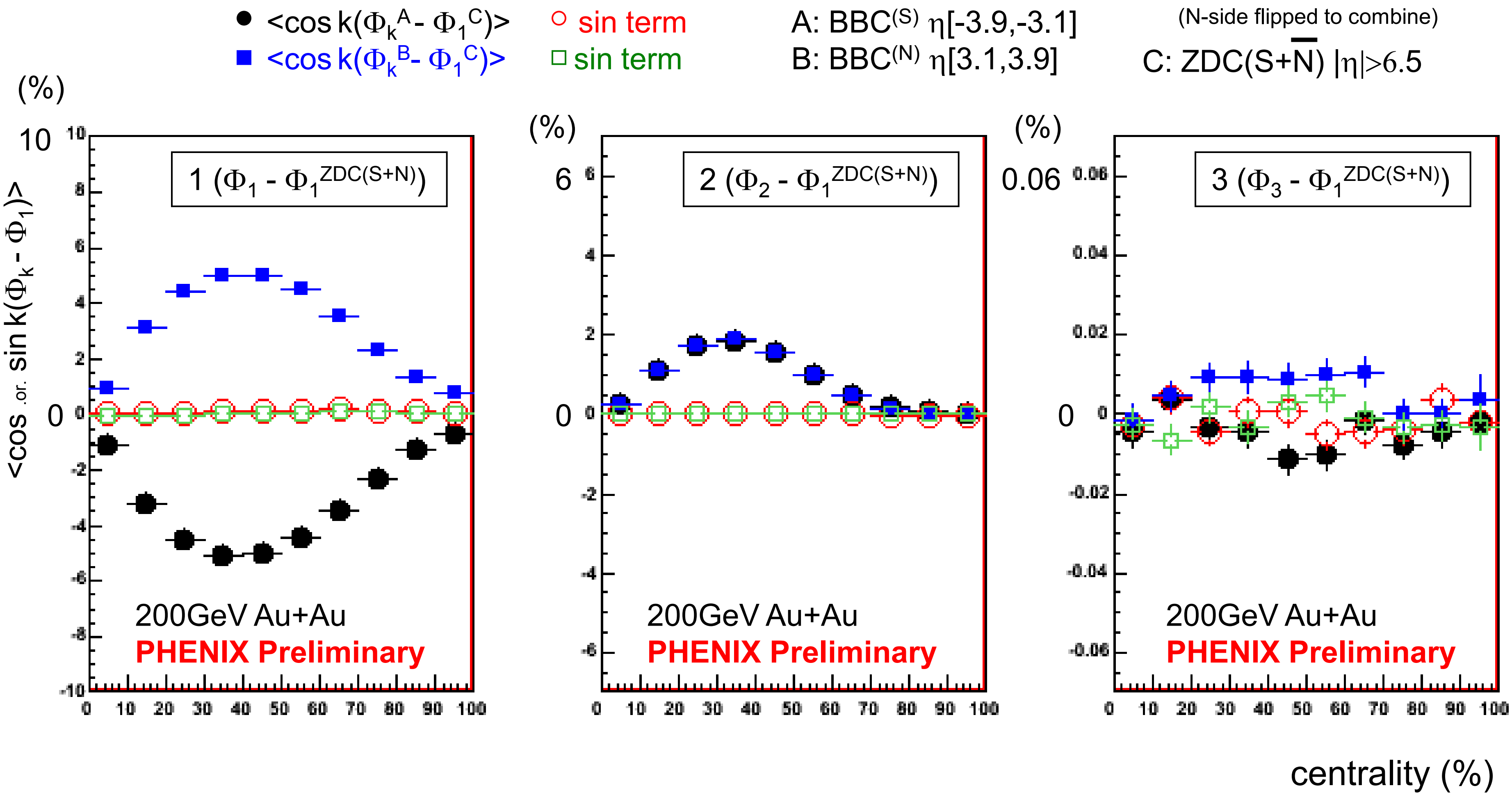
arXiv:1105.NNNN

200GeV Au+Au

A: RXN$^{(N,\eta>0)}$
B: BBC$^{(S,\eta<0)}$
C: MPC$^{(N,\eta>0)}$
D: MPC$^{(S,\eta<0)}$

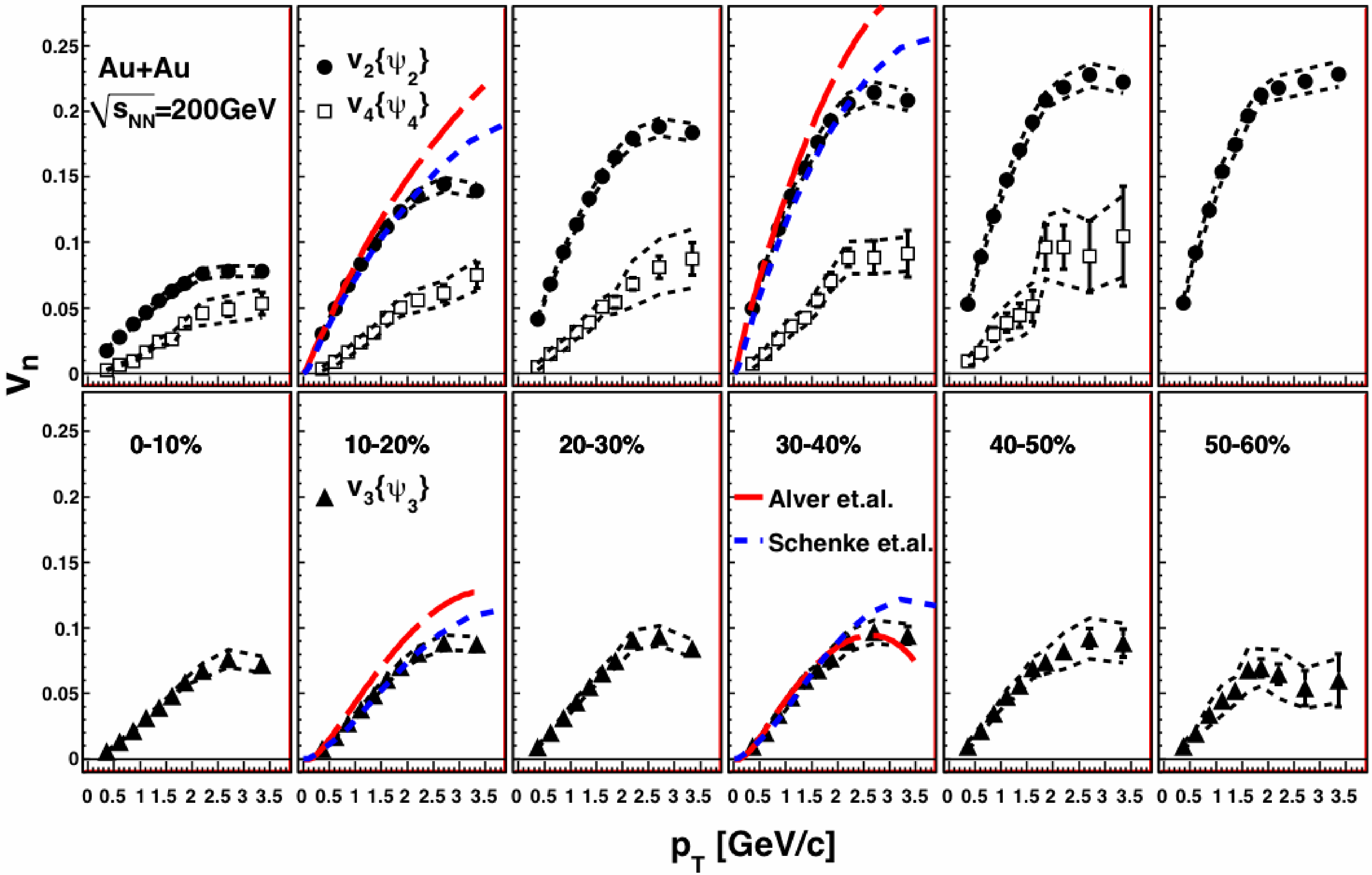
note:
x10 times scale difference between top and bottom.
Additional factor of x10 or x20 between left and right.

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



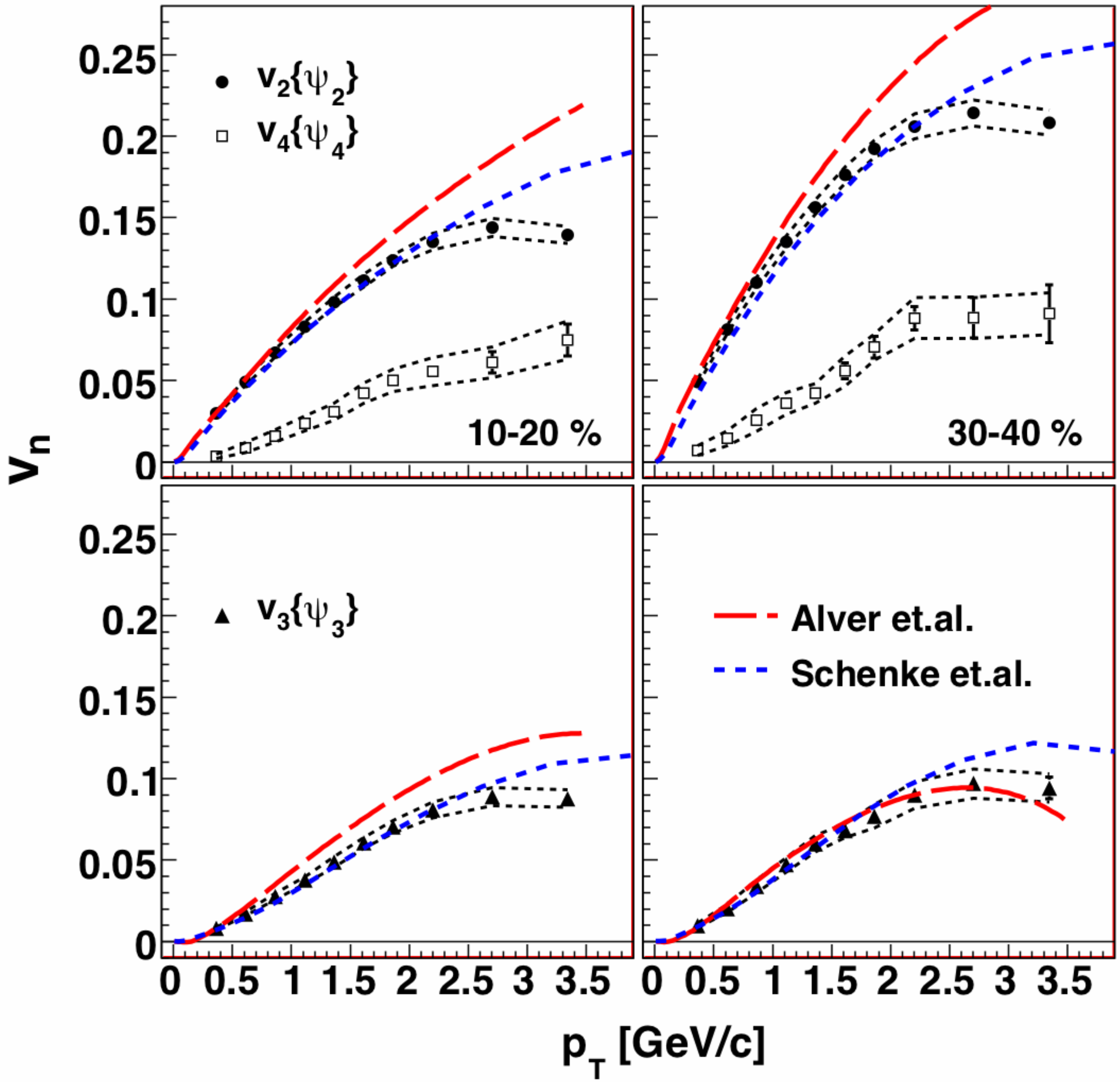
clear sign-flipping in v_1 , clear positive v_2

indication of sign-flipping in v_3 , sign(v_1) = sign(v_3)



Au+Au
$\sqrt{s_{NN}}$=200GeV
$v_2\{\psi_2\}$
$v_4\{\psi_4\}$
$v_3\{\psi_3\}$
0-10%
10-20%
20-30%
30-40%
40-50%
50-60%
Alver et.al.
Schenke et.al.
v_n
p_T [GeV/c]

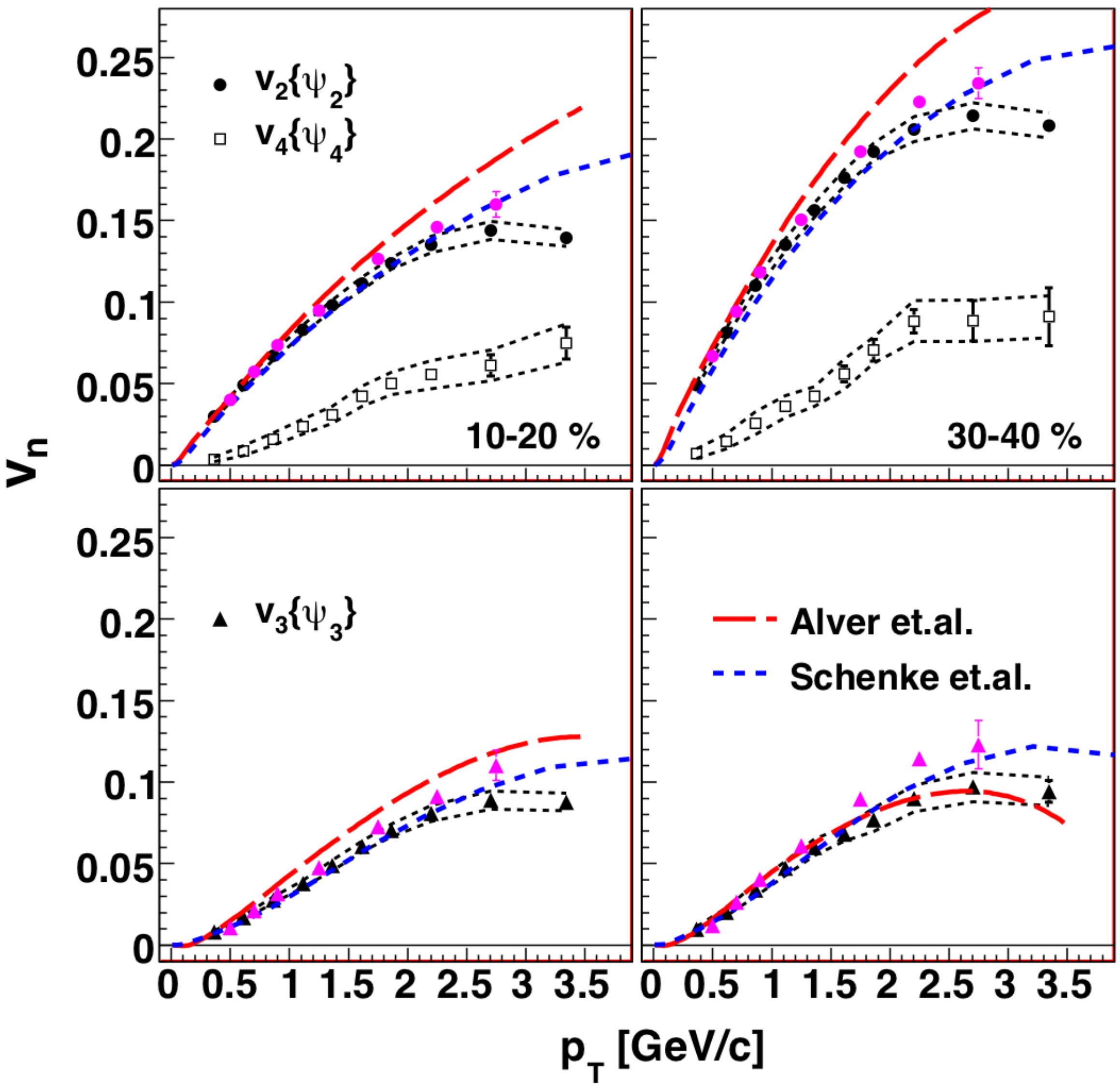
comparison with theory calculations at 200GeV Au+Au



arXiv:1105.NNNN

200GeV Au+Au
charged particle v_n

Hydro-models succeed with Glauber initial fluctuation.

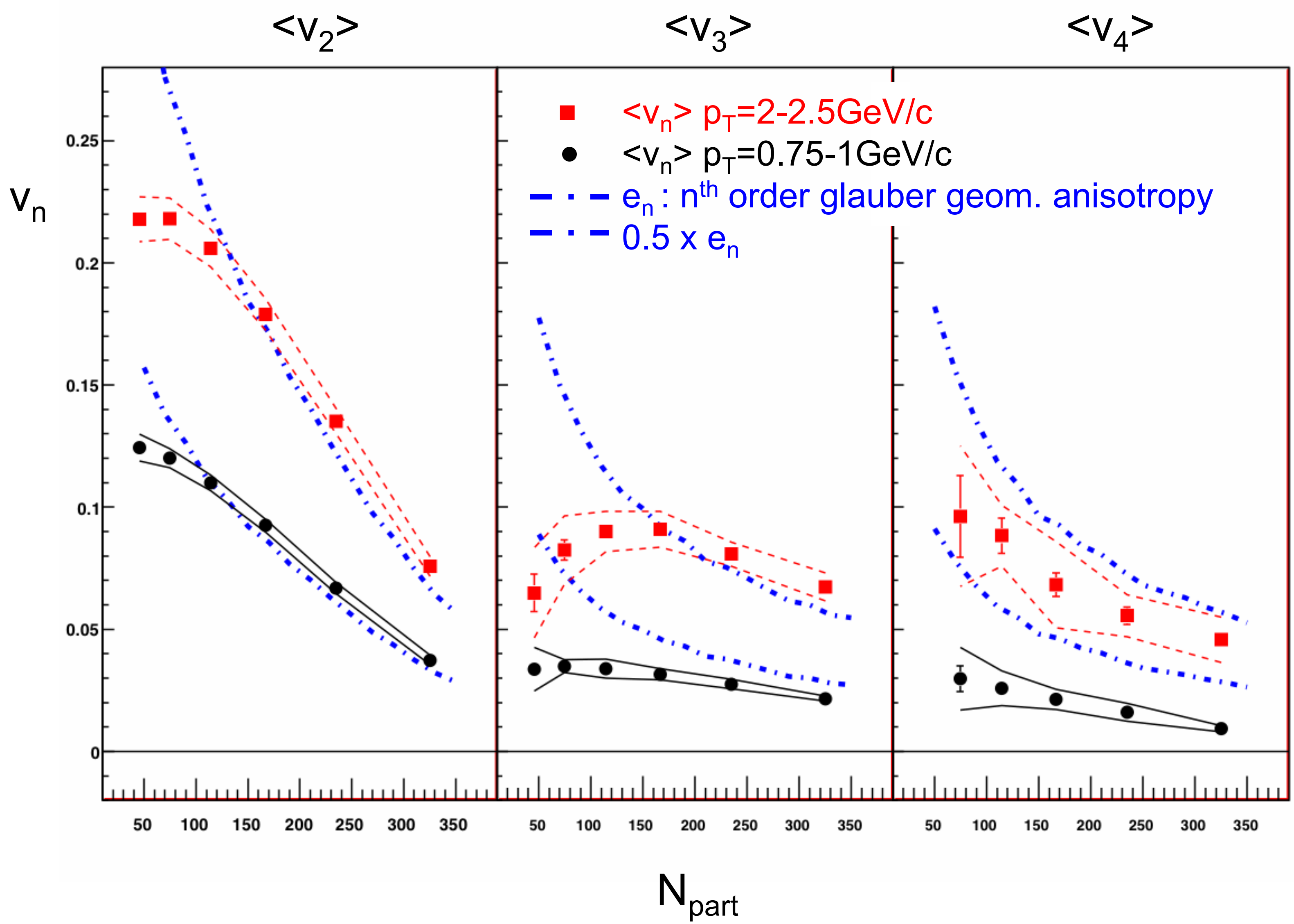


2-particle correlation within central arm $|\Delta\eta|<0.35$ also gives similar v_2 and v_3 with some small increase at higher p_T from non-flow jet bias ($|\Delta\eta|=0.3\sim0.7$)

v2 **v3**

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

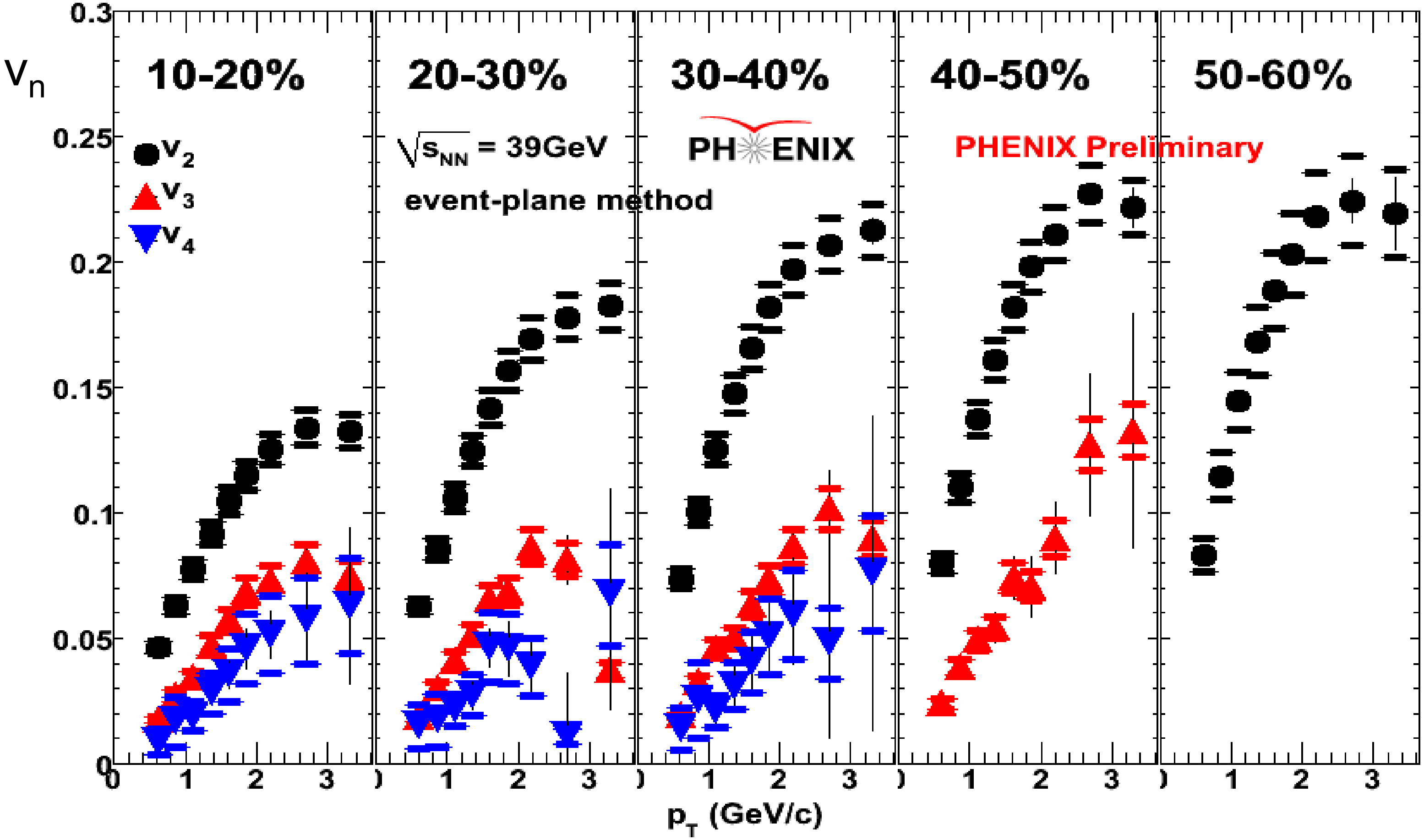
B. Alver et. al., Phys. Rev. C82, 034913(2010).
B. Schenke et. al., Phys. Rev. Lett. 106, 042301(2011).

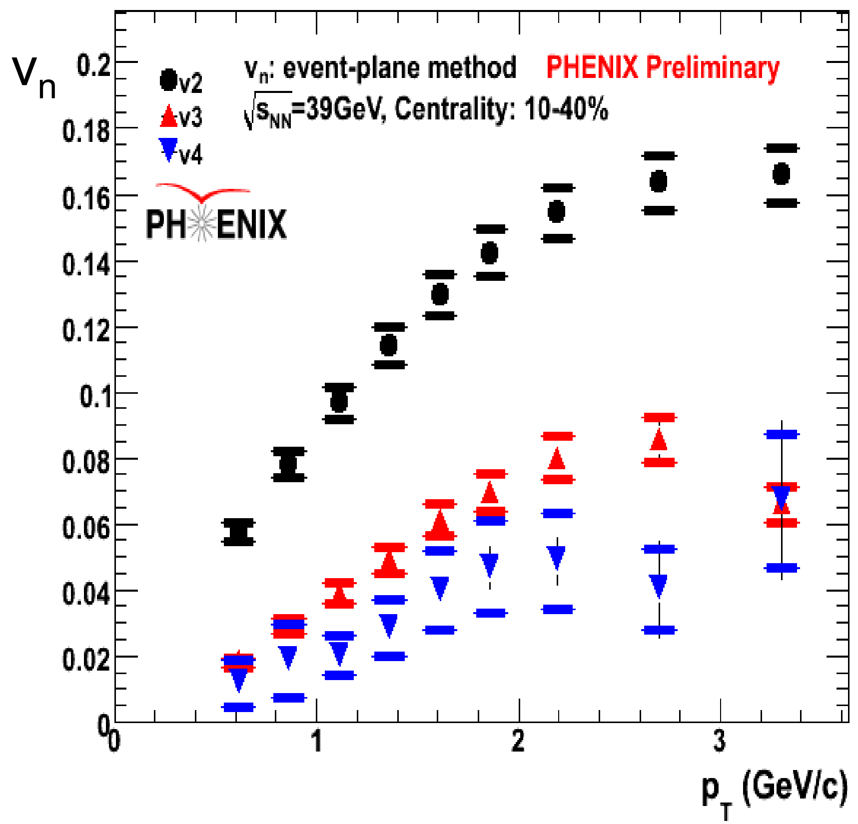


<v2>
<v3>
<v4>
vn
<vn> pT=2-2.5GeV/c
<vn> pT=0.75-1GeV/c
en : nth order glauber geom. anisotropy
0.5 x en
0.25
0.2
0.15
0.1
0.05
0
50 100 150 200 250 300 350
Npart

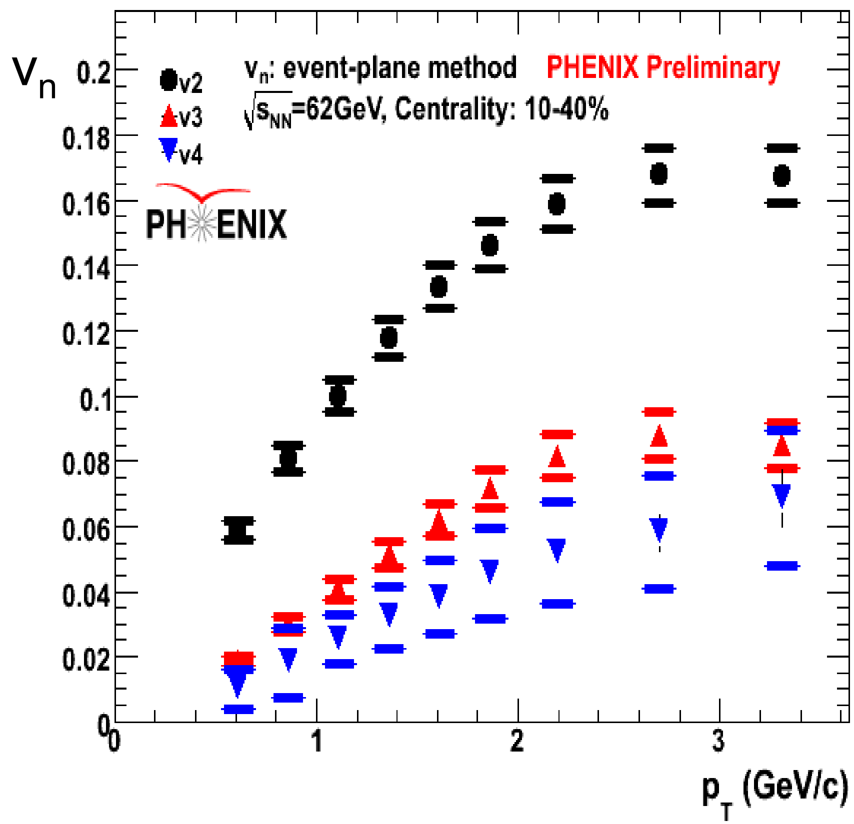
$v_2\{\Phi_2\}$, $v_3\{\Phi_3\}$, $v_4\{\Phi_4\}$ at 39GeV Au+Au

charged particle v_n : $|\eta|<0.35$
reaction plane Φ_n : $|\eta|=1.0\sim2.8$

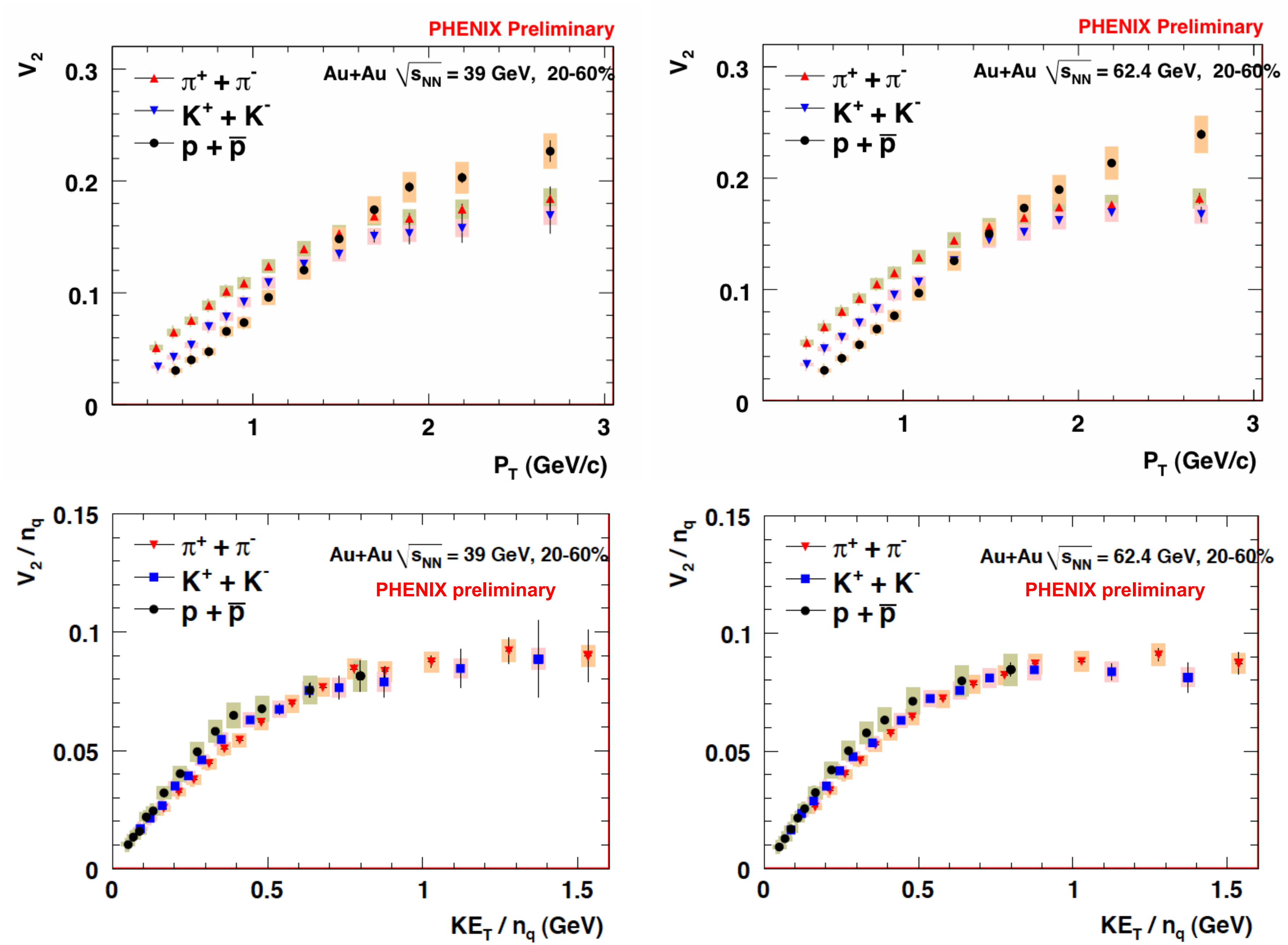


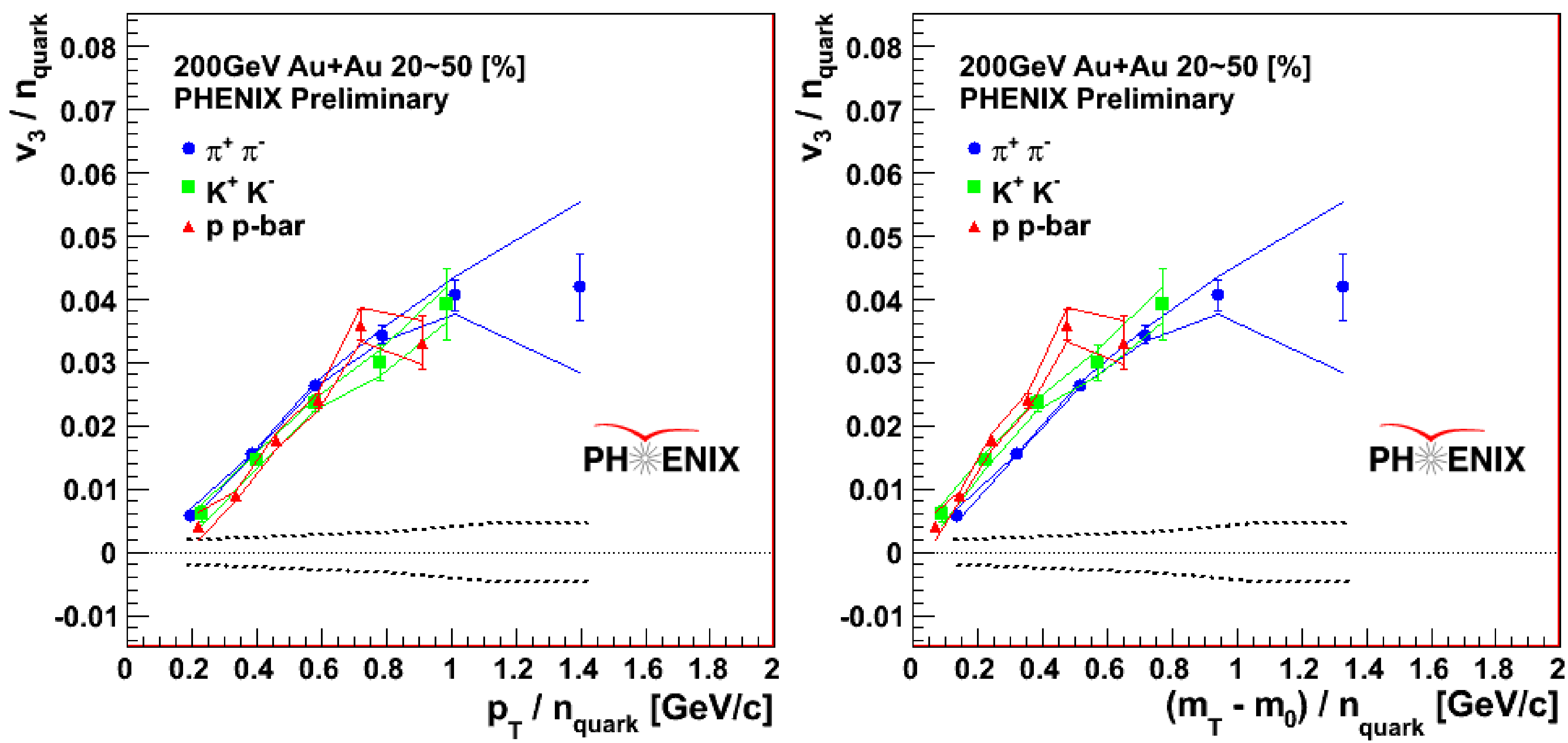


v_n
v2
v3
v4
v_n: event-plane method
PHENIX Preliminary
√s_NN=39GeV, Centrality: 10-40%
PHENIX
0.2
0.18
0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
0
1
2
3
p_T (GeV/c)



v_n
v2
v3
v4
v_n: event-plane method
PHENIX Preliminary
√s_NN=62GeV, Centrality: 10-40%
PHENIX
0.2
0.18
0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
0
1
2
3
p_T (GeV/c)


PHENIX Preliminary
Au+Au $\sqrt{s_{NN}}$ = 39 GeV, 20-60%
$\pi^+ + \pi^-$
$K^+ + K^-$
$p + \bar{p}$
v_2
P_T (GeV/c)
PHENIX Preliminary
Au+Au $\sqrt{s_{NN}}$ = 62.4 GeV, 20-60%
$\pi^+ + \pi^-$
$K^+ + K^-$
$p + \bar{p}$
v_2
P_T (GeV/c)
Au+Au $\sqrt{s_{NN}}$ = 39 GeV, 20-60%
PHENIX preliminary
v_2 / n_q
KE_T / n_q (GeV)
Au+Au $\sqrt{s_{NN}}$ = 62.4 GeV, 20-60%
PHENIX preliminary
v_2 / n_q
KE_T / n_q (GeV)


200GeV Au+Au 20~50 [%]
PHENIX Preliminary
π+ π-
K+ K-
p p-bar
PHENIX
v3 / nquark
pT / nquark [GeV/c]
(mT - m0) / nquark [GeV/c]

Method of event plane determination

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

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

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

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

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

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

(3) n-th harmonics reaction plane

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

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

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

(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 dϕ 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(Hit) and v_n^B(Hit) can be determined as a function of centrality

(5) v_n^C(Track) can be determined as a function of centrality and p_T

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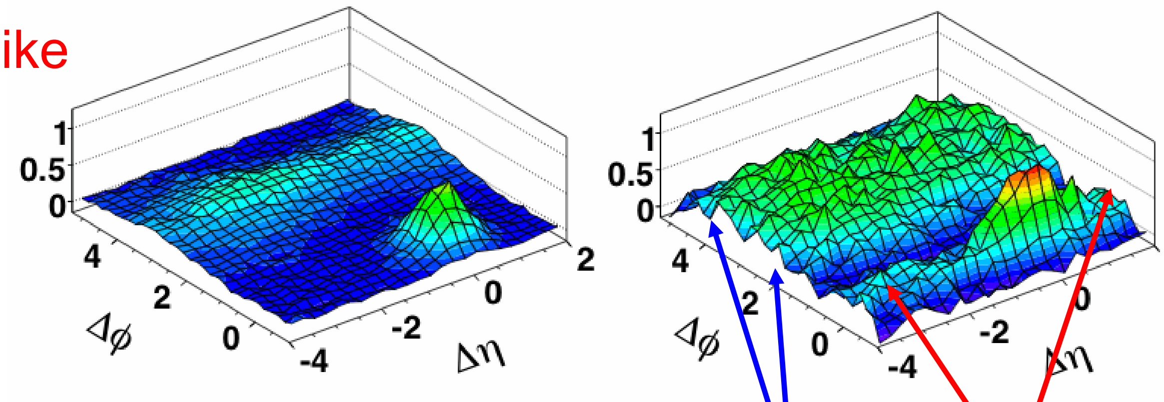
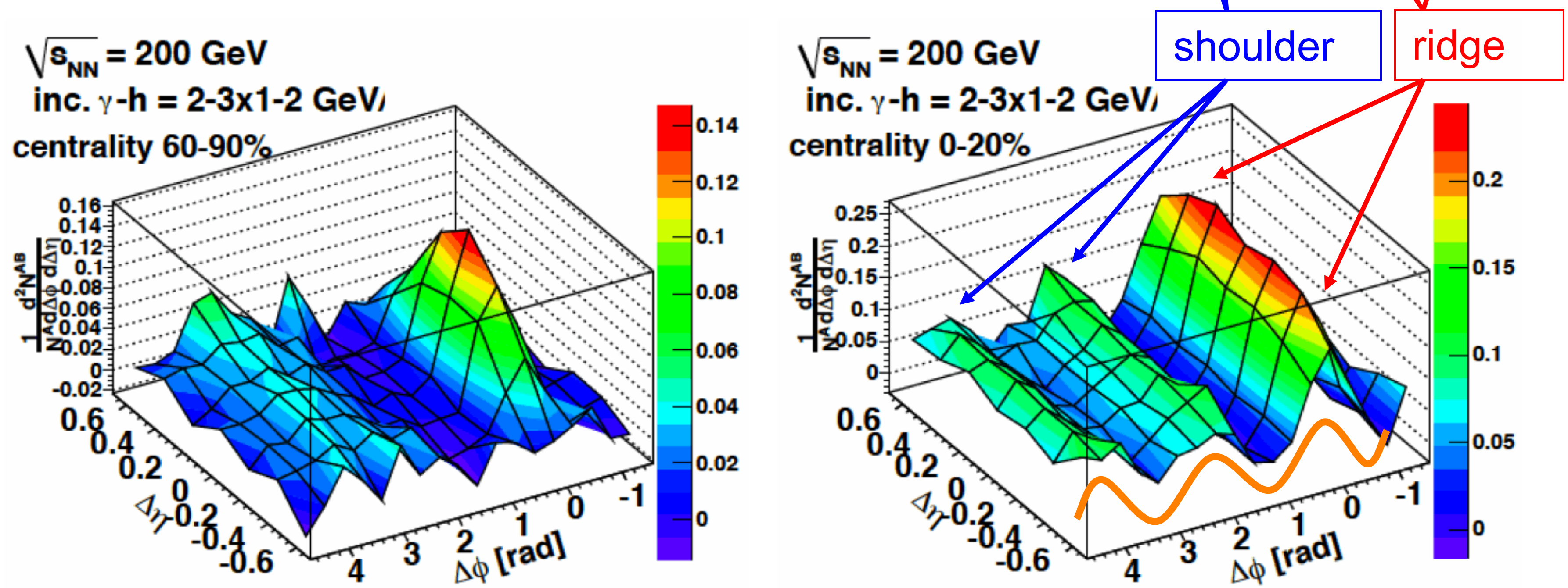
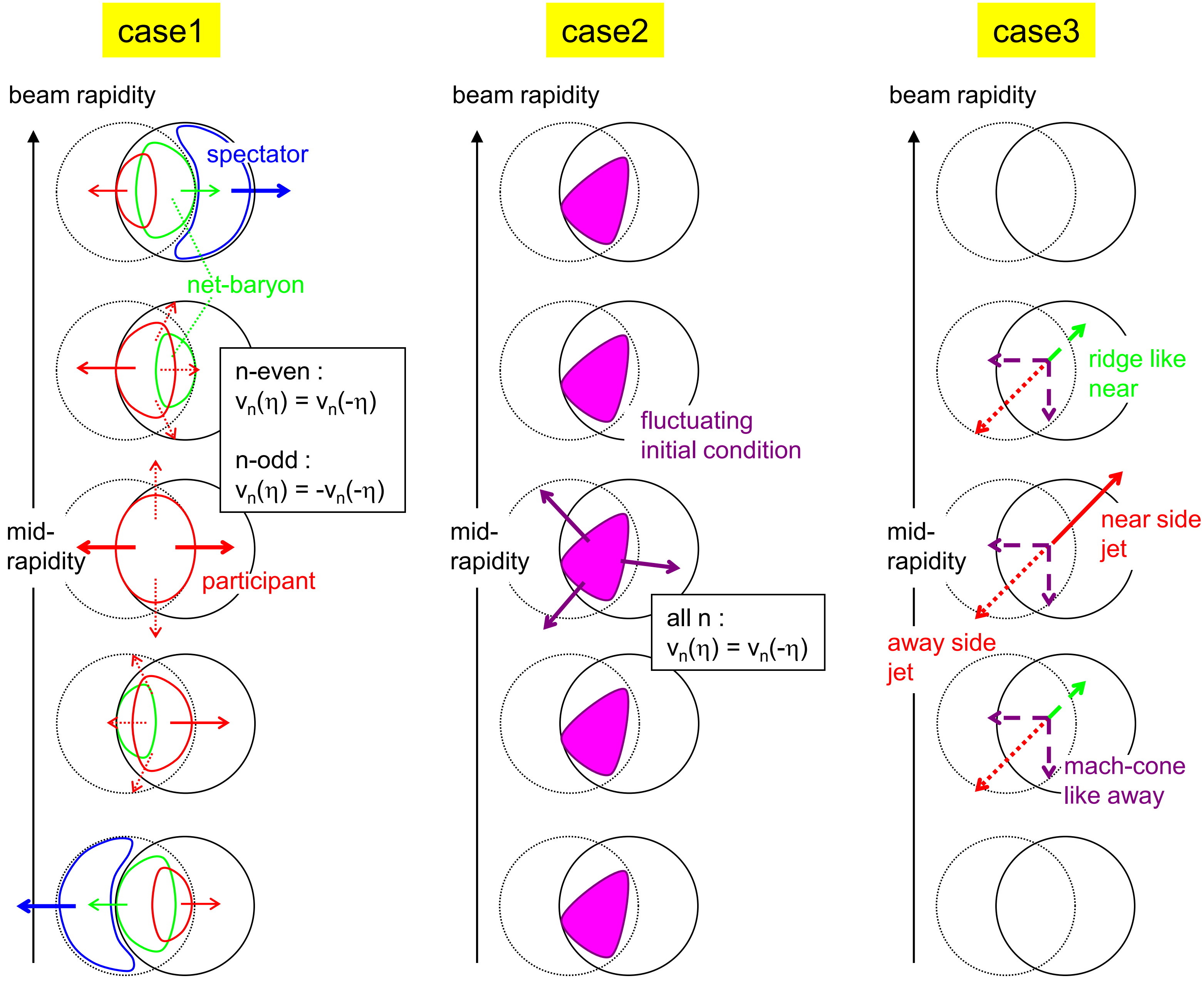
Some couplings between "mach-cone-like and ridge-like emissions" and v_3 are expected to be there!

What is the origin and
what is the consequence?

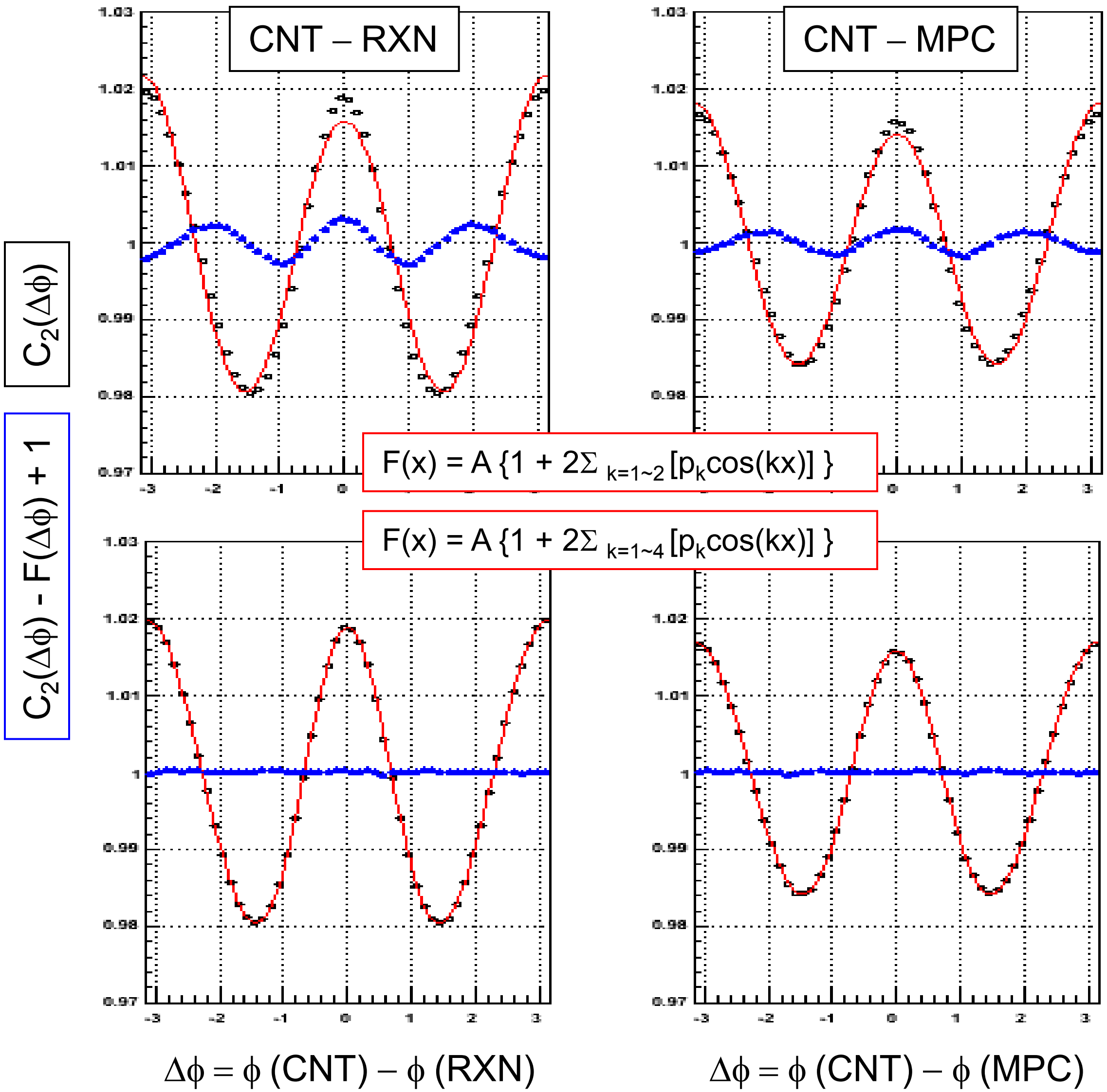


(a) p+p PYTHIA (version 6.325)
(b) Au+Au 0-30% (PHOBOS)




case1
case2
case3
beam rapidity
beam rapidity
beam rapidity
spectator
net-baryon
n-even :
$v_n(\eta) = v_n(-\eta)$
n-odd :
$v_n(\eta) = -v_n(-\eta)$
mid-
rapidity
participant
fluctuating
initial condition
mid-
rapidity
all n :
$v_n(\eta) = v_n(-\eta)$
ridge like
near
mid-
rapidity
near side
jet
away side
jet
mach-cone
like away

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=2~4(GeV/c)

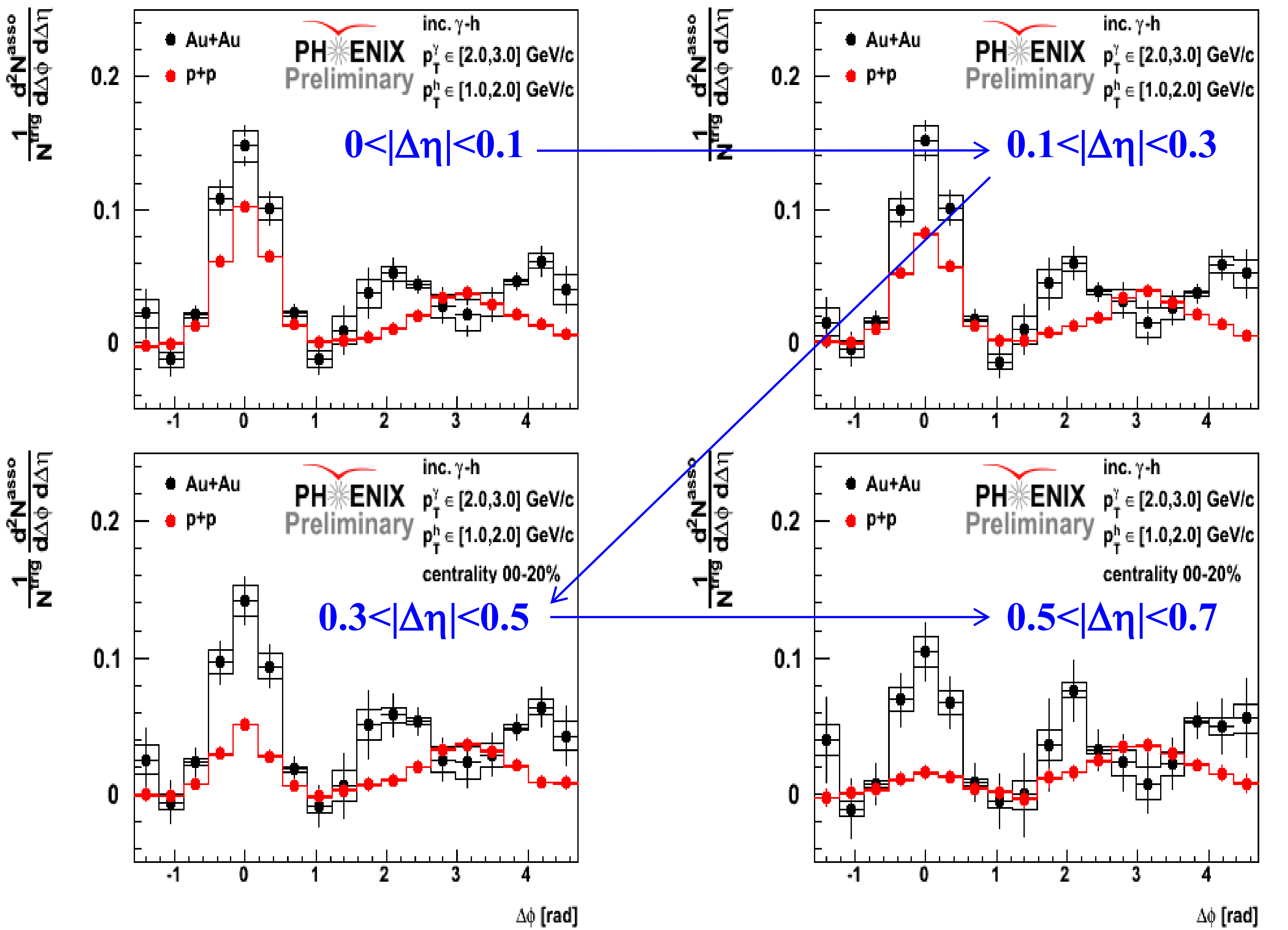
RXN: reaction plane detector
forward $|\eta|$=1.0~2.8
all cells/hits (charge weighting with Pb converter)

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

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

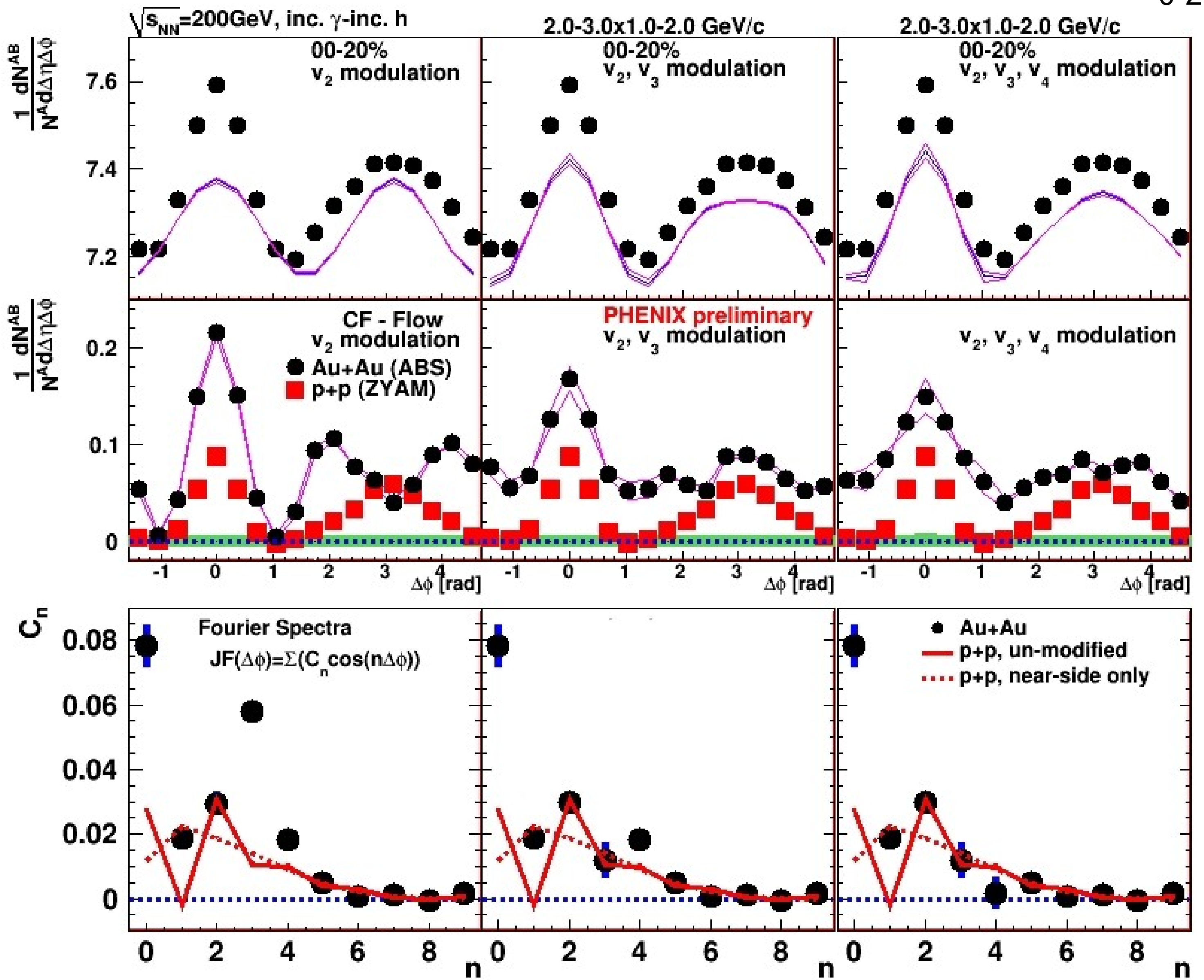
clear 3rd moment in two-particle correlation with large η gap central-central 2-part. correlation with $\Delta\eta$ dependence

200GeV Au+Au
0-20%, inc. γ-had.



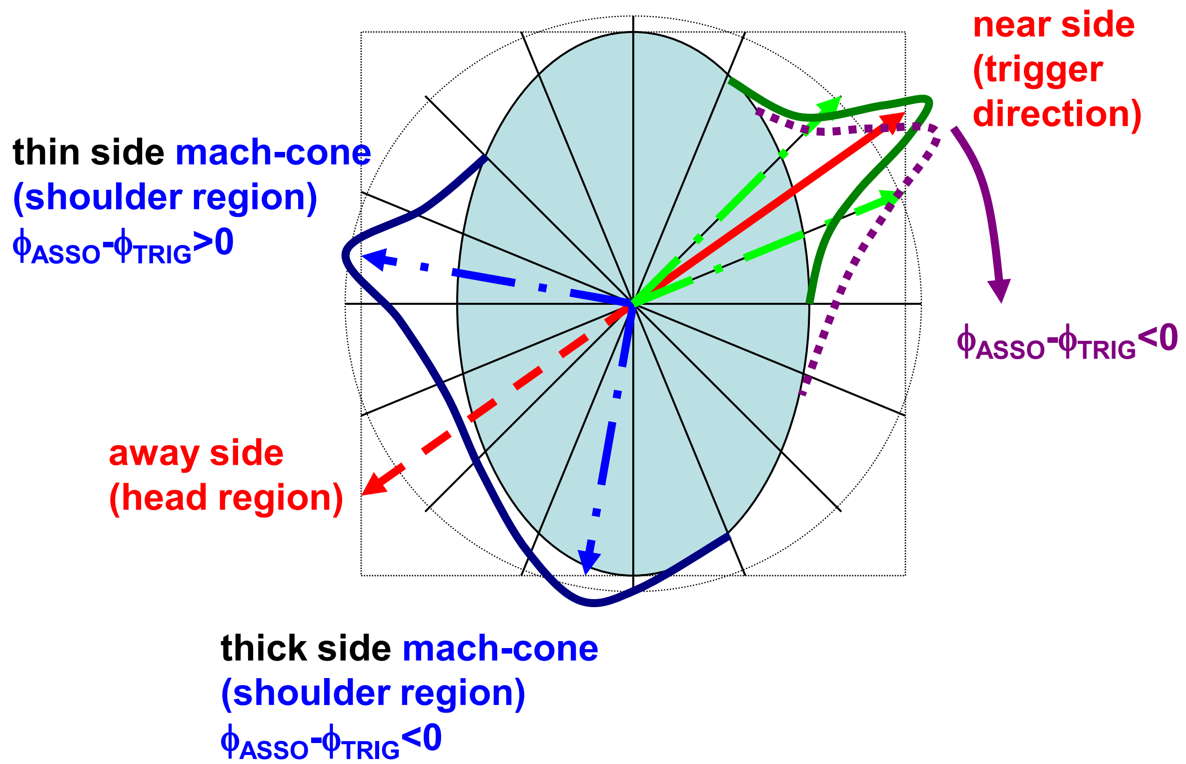
flow subtraction with measured v_n for cent-cent 2-par. correlation

200GeV Au+Au
0-20%, inc. γ-had.

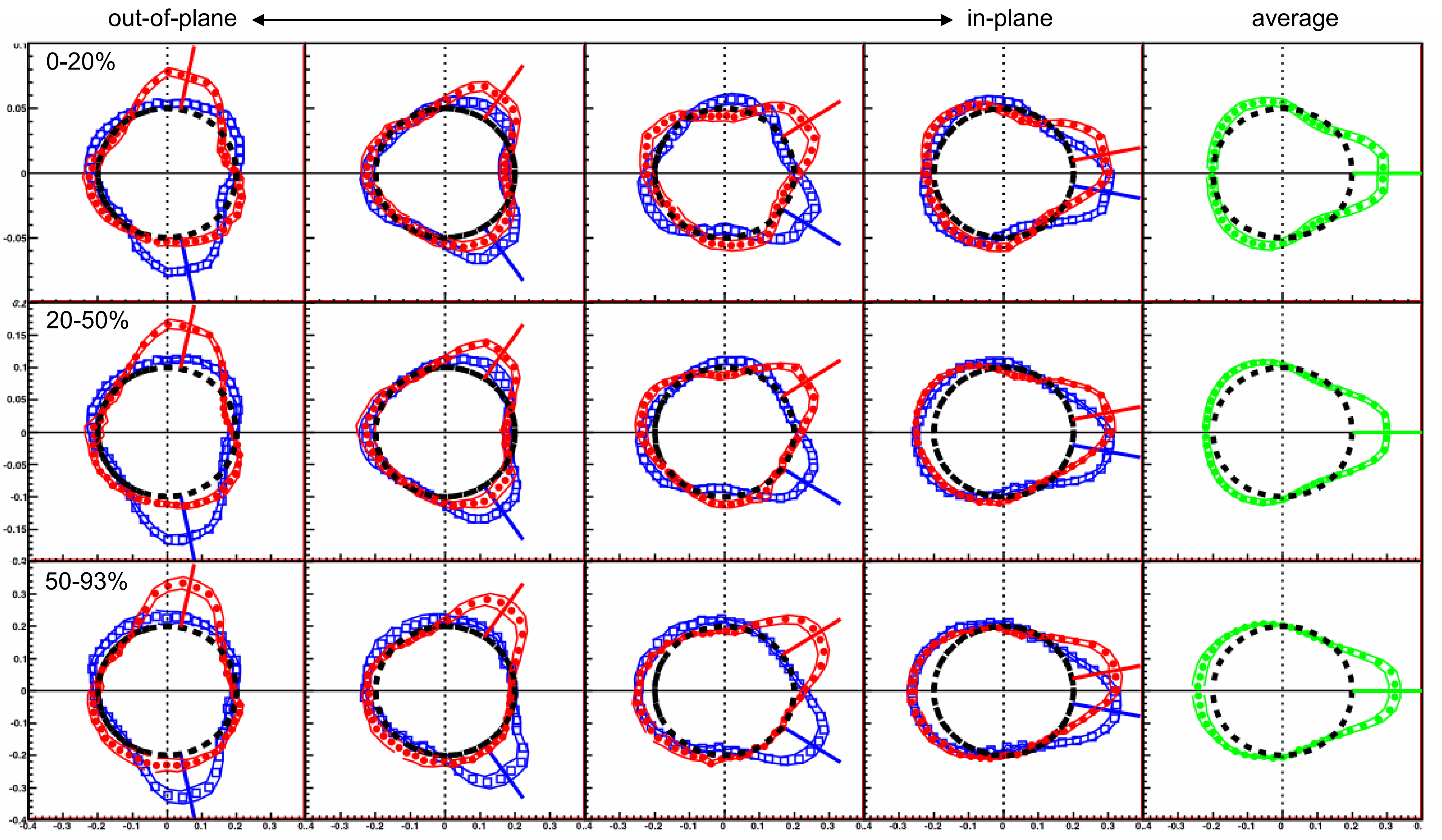


Fourier spectra of extracted jet shape

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

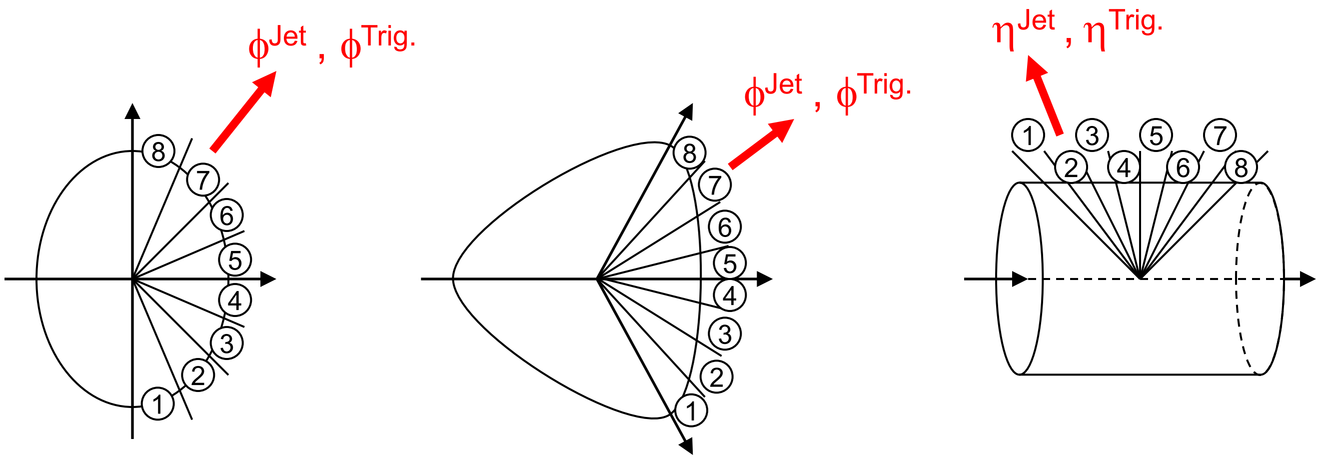


Flow subtracted 2-particle ΔΦ correlation with trigger angle selection in 200GeV Au+Au

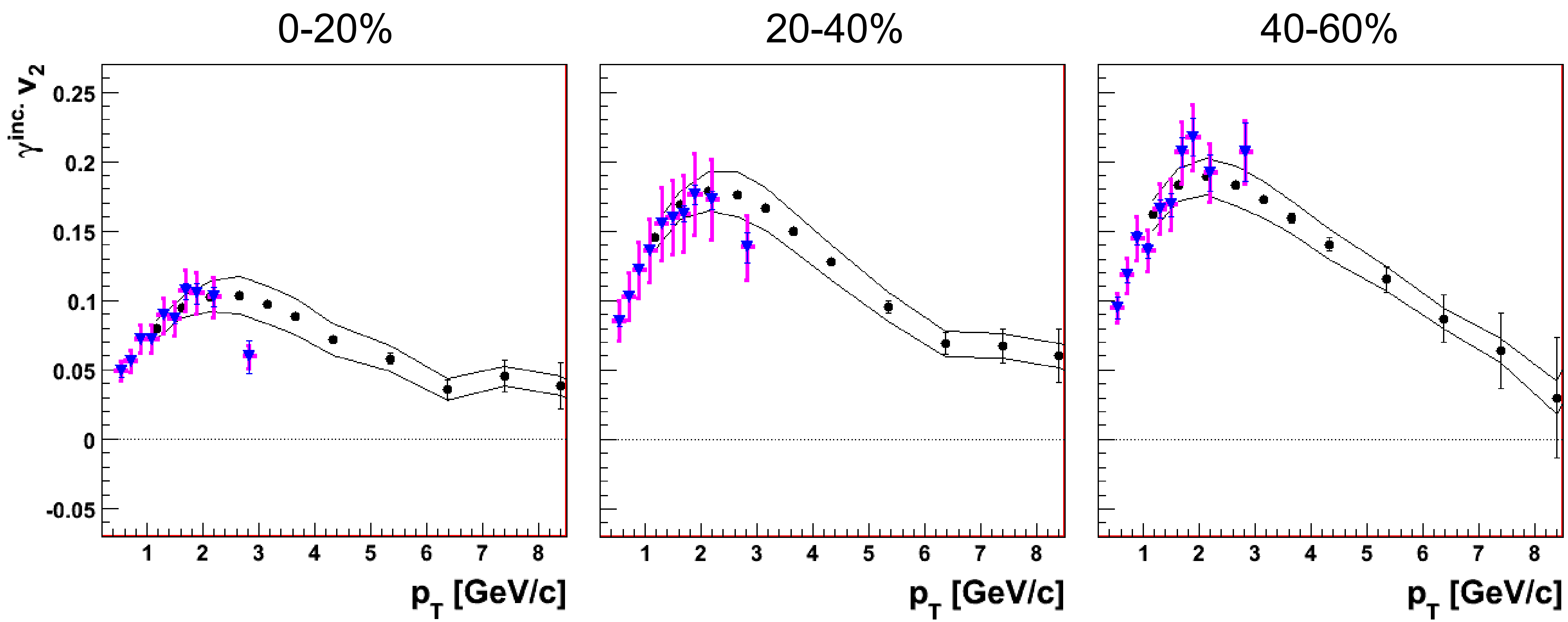


200GeV Au+Au -> h-h (p_T^{Trig}=2~4GeV/c, p_T^{Asso}=1~2GeV/c)
$v_2(v_4\{\Phi_2\})$-only subtraction **PHENIX preliminary**

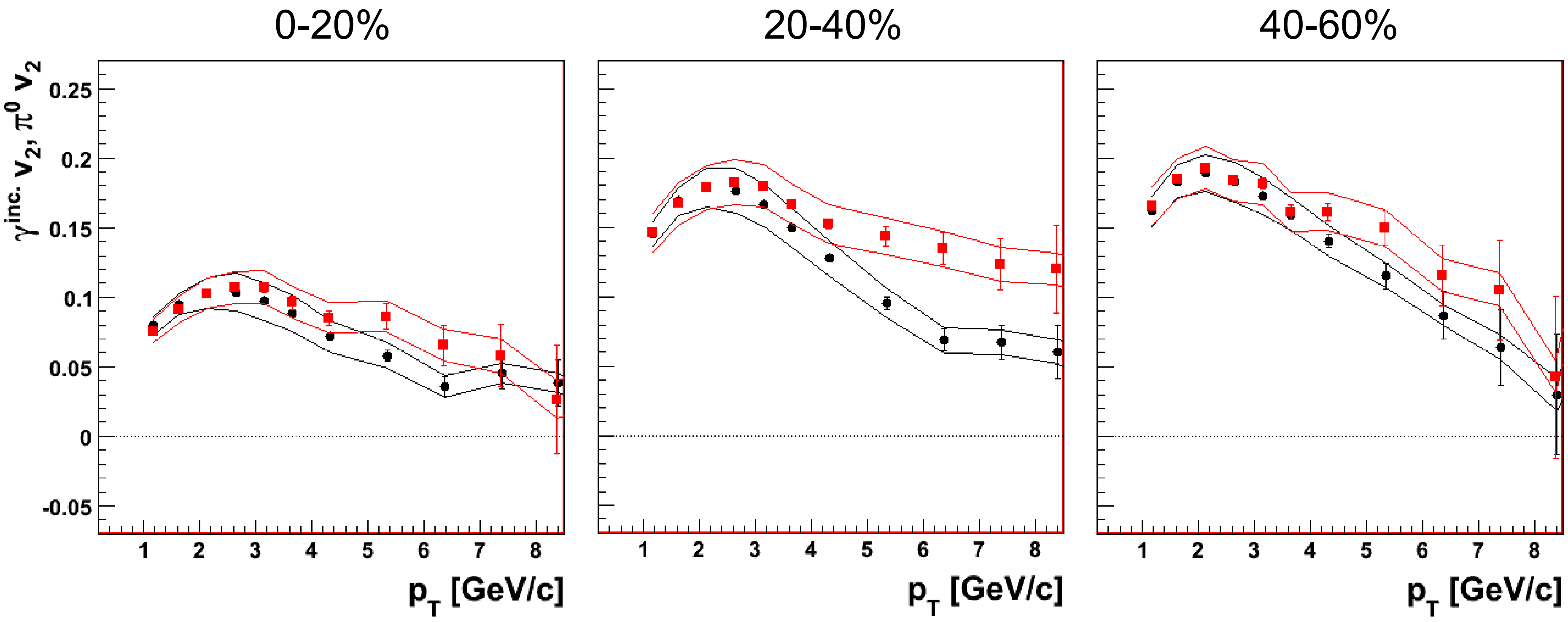
jet, di-jet and multi-particle correlation with various conditions



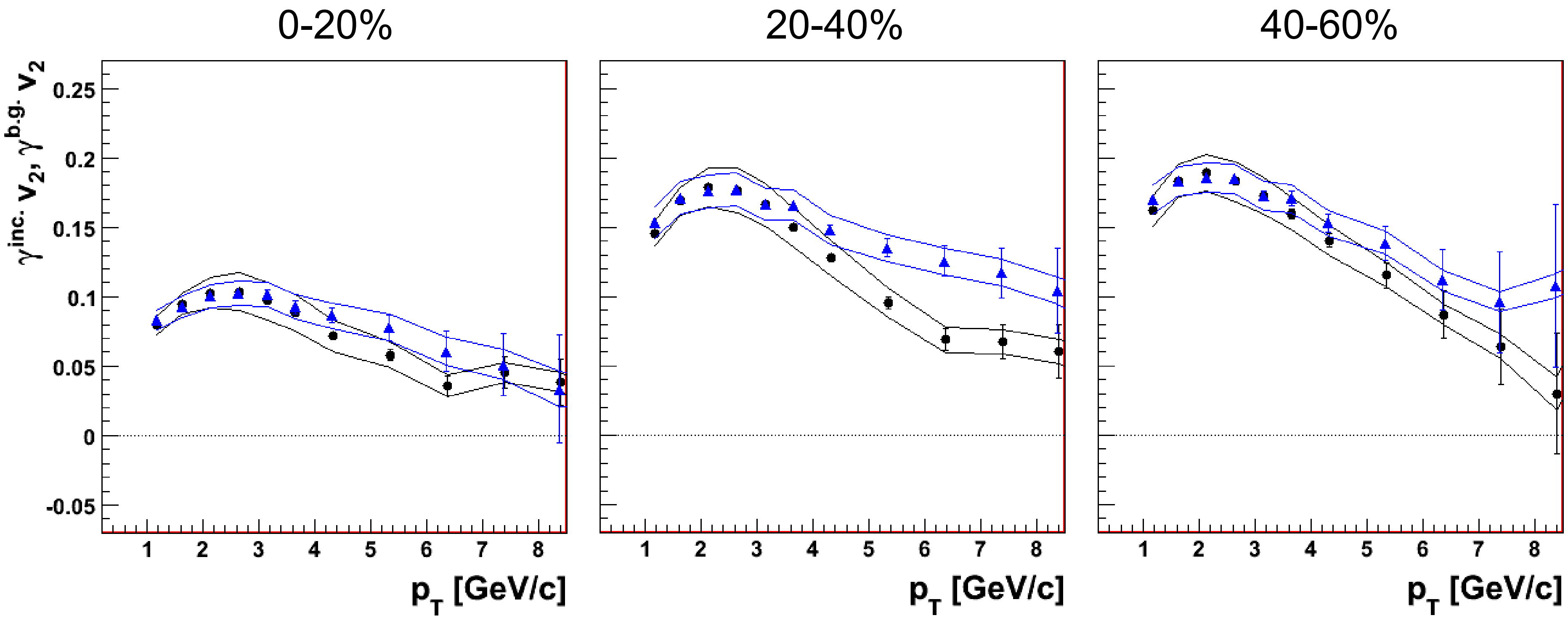
real photon v_2 and external conversion photon v_2



Inclusive photon v_2 and π^0 v_2

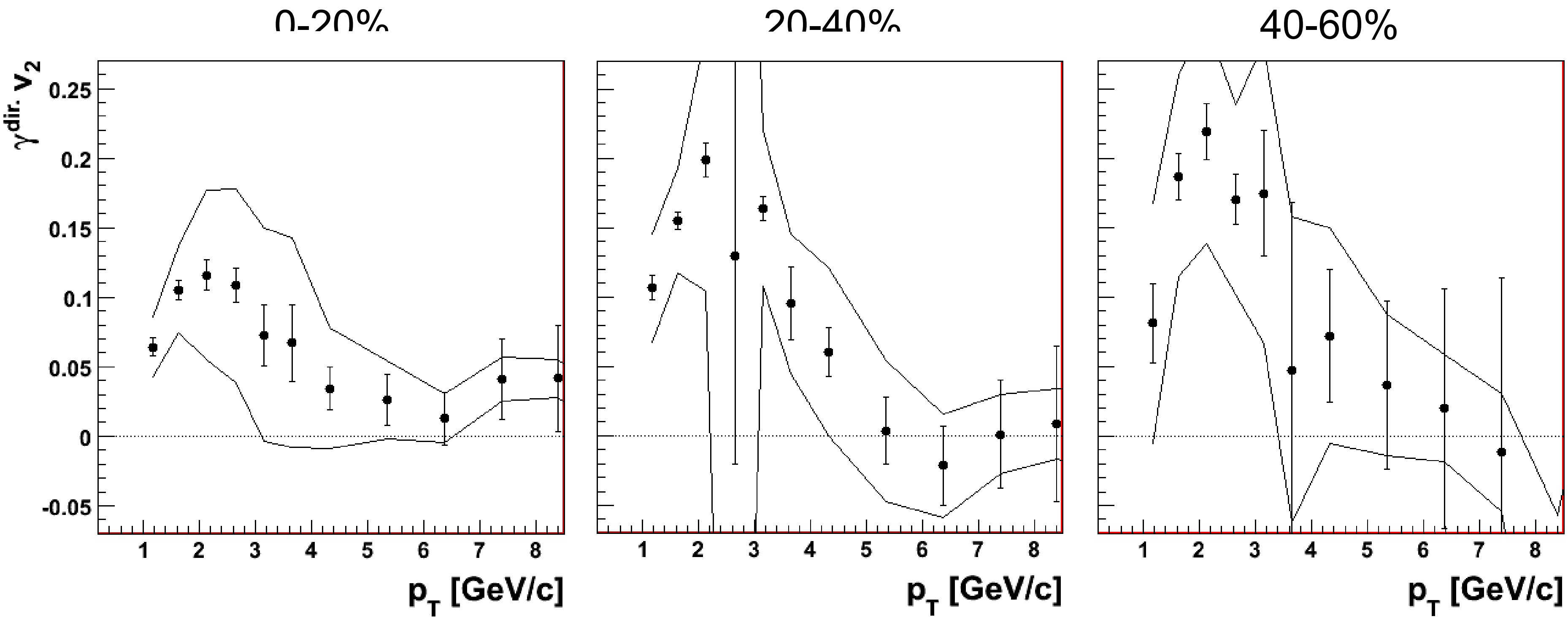


Inclusive photon v_2 and decay photon v_2



200GeV Au+Au

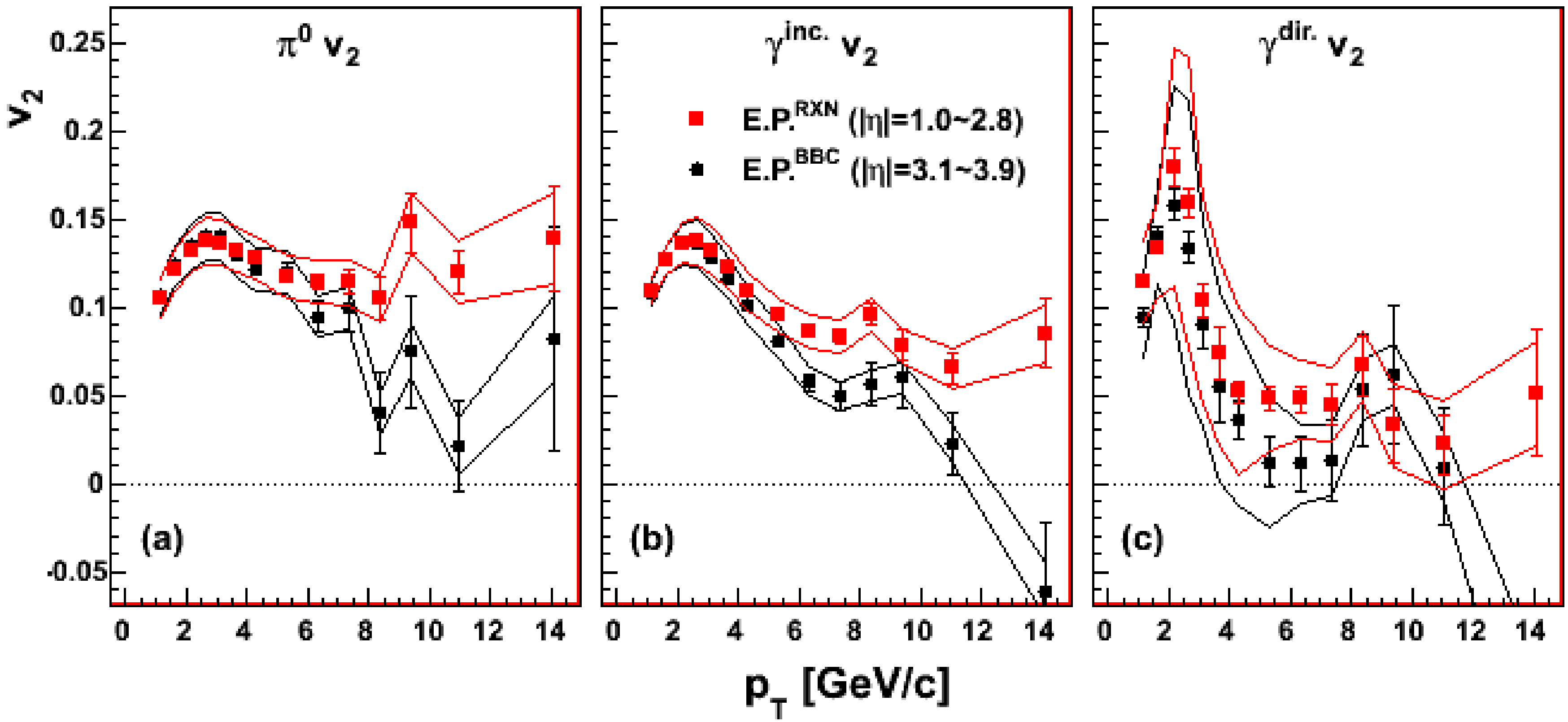
direct photon v_2



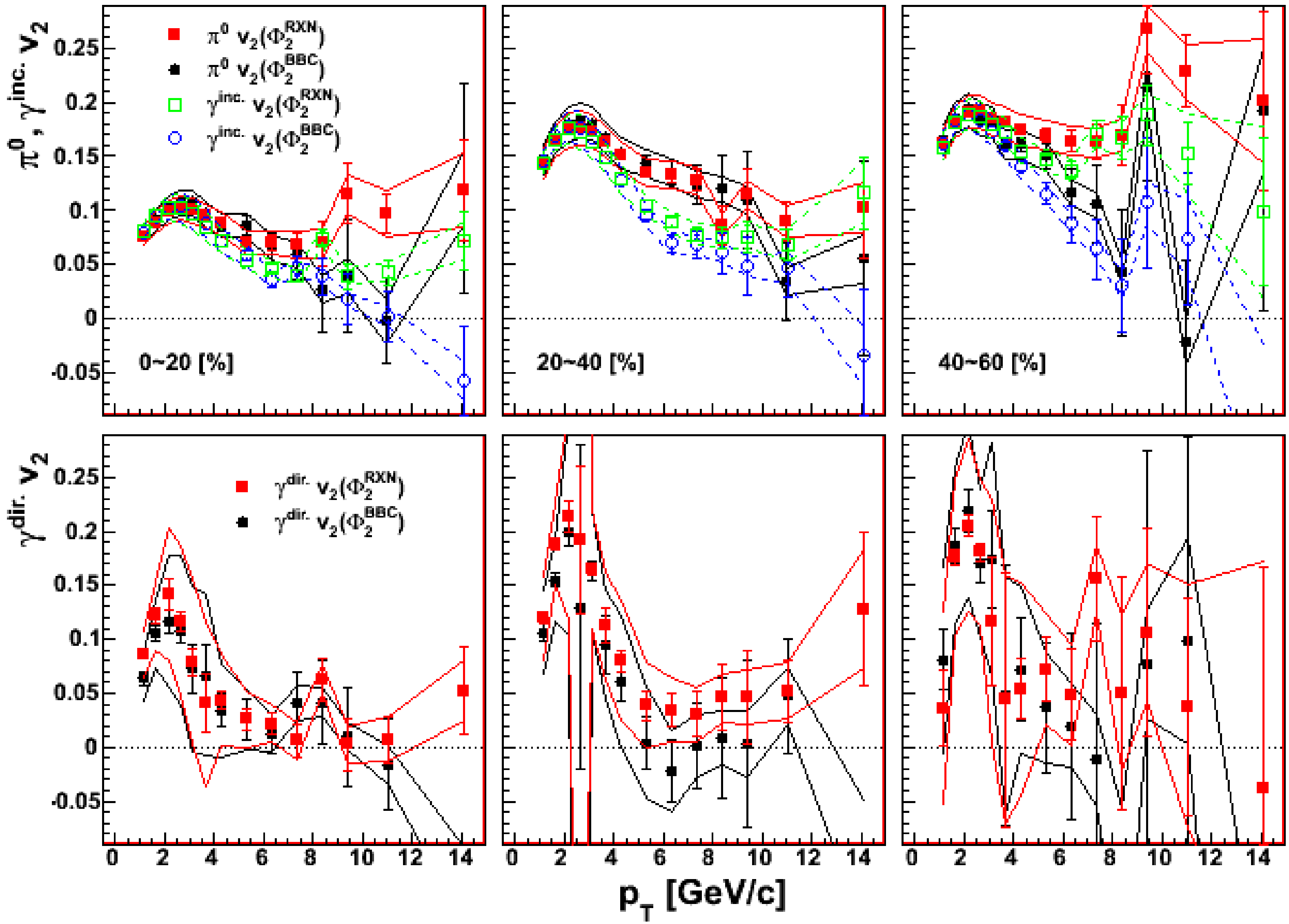
π^0, $\gamma^{inclusive}$, γ^{direct} v_2

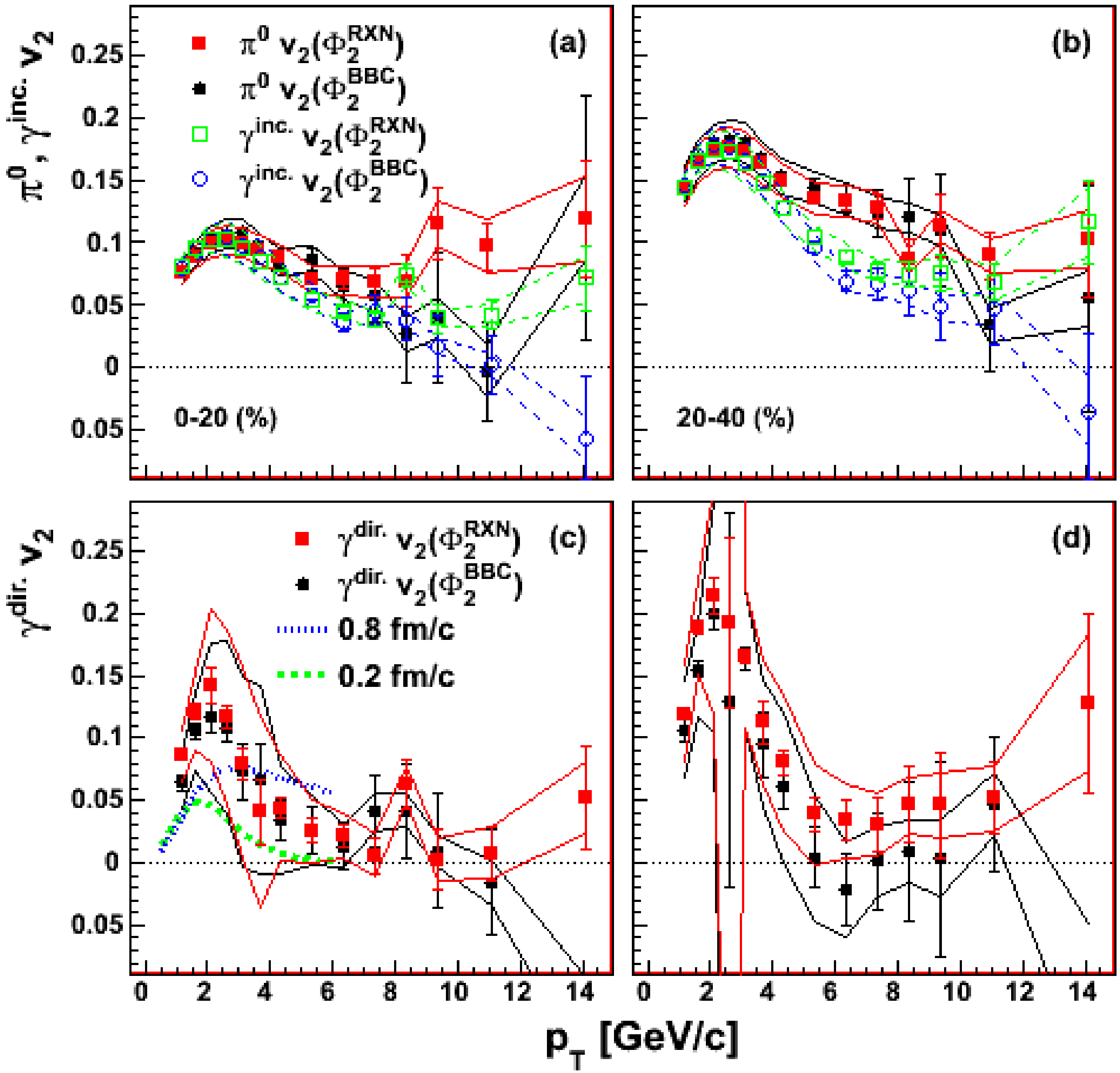
200GeV Au+Au (min. bias)

arXiv:1105.NNNN

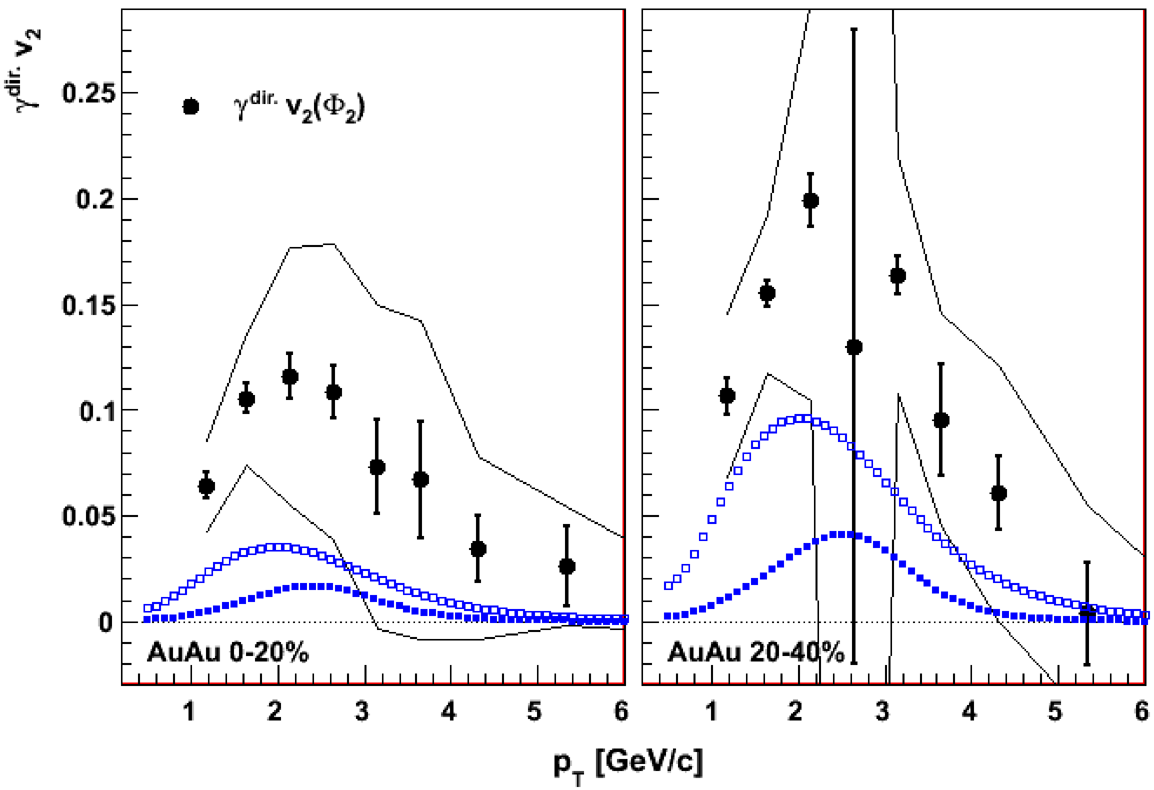


similar to hadron v2 at low pT
much smaller v2 at high pT

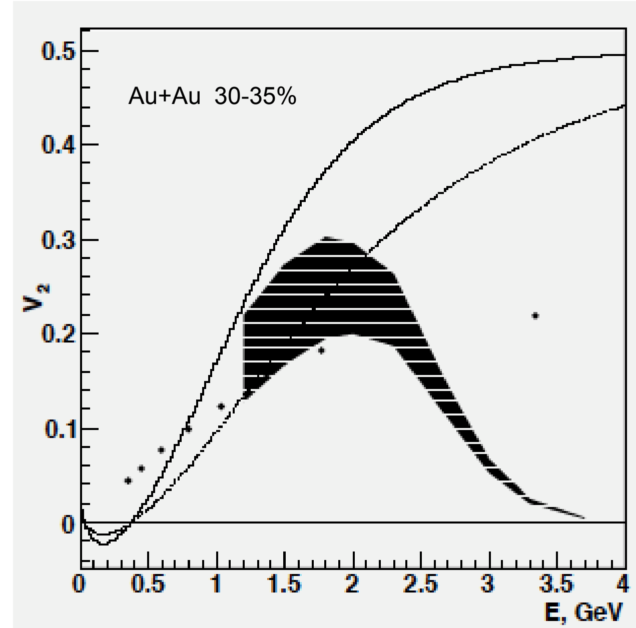

$\pi^0 v_2(\Phi_2^{RXN})$
$\pi^0 v_2(\Phi_2^{BBC})$
$\gamma^{inc.} v_2(\Phi_2^{RXN})$
$\gamma^{inc.} v_2(\Phi_2^{BBC})$
$\pi^0, \gamma^{inc.} v_2$
0~20 [%]
20~40 [%]
40~60 [%]
$\gamma^{dir.} v_2(\Phi_2^{RXN})$
$\gamma^{dir.} v_2(\Phi_2^{BBC})$
$\gamma^{dir.} v_2$
p_T [GeV/c]



π⁰, γ^inc. v₂
π⁰ v₂(Φ₂^RXN)
π⁰ v₂(Φ₂^BBC)
γ^inc. v₂(Φ₂^RXN)
γ^inc. v₂(Φ₂^BBC)
(a)
(b)
0-20 (%)
20-40 (%)
γ^dir. v₂
γ^dir. v₂(Φ₂^RXN)
γ^dir. v₂(Φ₂^BBC)
0.8 fm/c
0.2 fm/c
(c)
(d)
p_T [GeV/c]



Holopainen, Räsänen, Eskola
arXiv:1104.5371v1



V. S. Pantuev
arXiv:1105.4033v1