PHENIX Reaction Plane Studies

Winter Workshop on Nuclear Dynamics
2010
Ocho Rios, Jamaica

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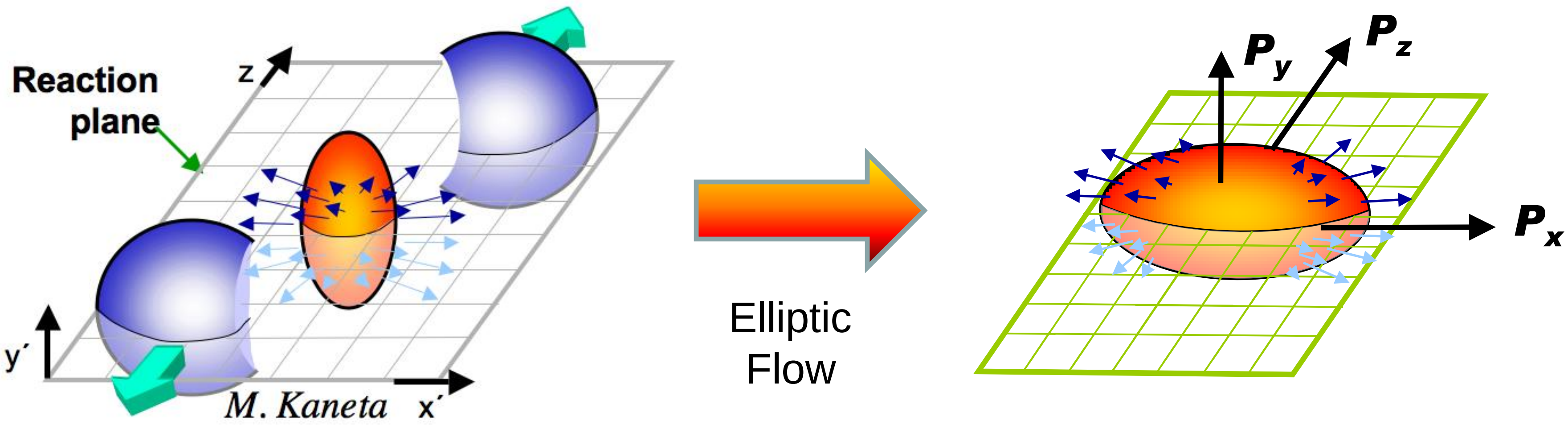
- Introduction
  - The reaction plane
  - PHENIX detectors
- Results
  - Low-p_T
  - High-p_T
  - Azimuthal Correlations
  - Heavy flavor and Forward Rapidities
- Summary

Reaction Plane and Elliptic Flow



Spatial anisotropy

Momentum anisotropy

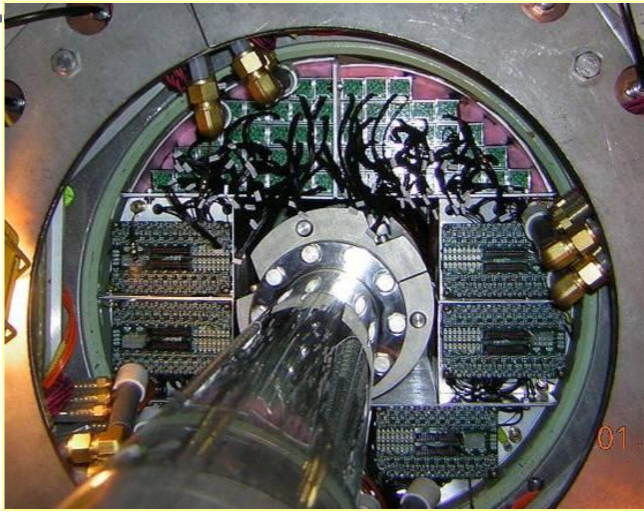
Fourier expansion of the distribution of produced particle angle wrt reaction plane (Δϕ):

$$\frac{dN}{d\Delta\varphi} = N_0\left[1 + 2v_1\cos 2\Delta\varphi + 2v_2\cos 2\Delta\varphi + \cdots\right]$$

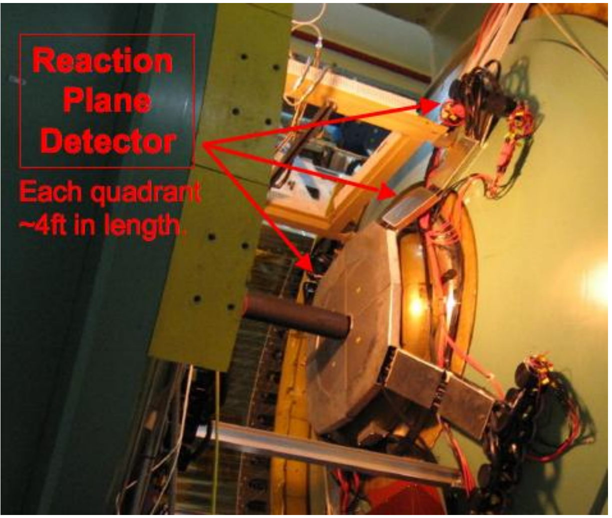
- Momentum anisotropy reflects the characteristics of the hot, dense medium
  - Small mean free path, thermalization, pressure gradients
- v_2 long considered a powerful probe for QGP studies

Multiple Overlapping and Complementary Detectors

Beam-Beam Counters
- Quartz Cherenkov radiators
- $3.0 < |\eta| < 4.0$
- All Runs



Muon Piston Calorimeter
- $PbWO_4$ PHOS crystals
- $3.1 < |\eta| < 3.7$
- New in Run 6



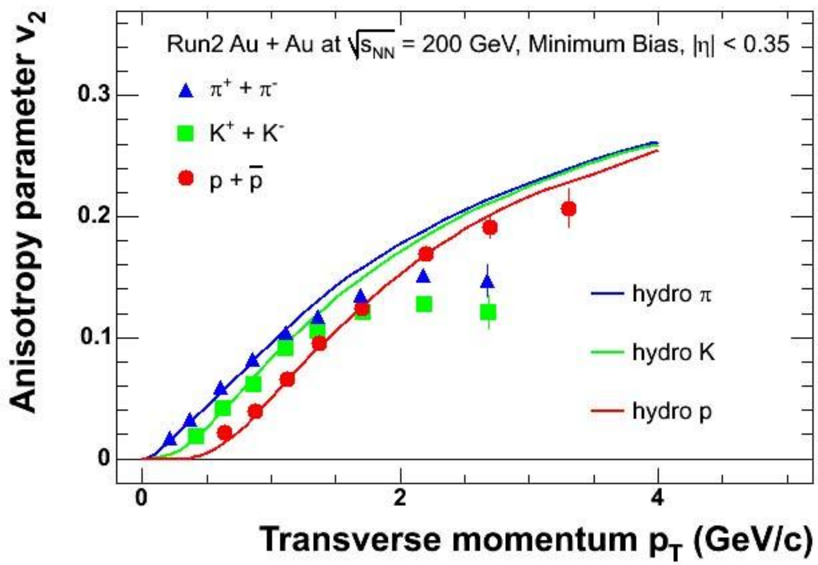
Reaction Plane Detector
- Plastic scintillators
- 12 segments in ϕ
- 2 segments in η
  - $1.0 < |\eta| < 1.5$
  - $1.5 < |\eta| < 2.8$
- New in Run 7

ZDC-SMD
- Scint. Strip
- $|\eta| \sim 6.5$
- All runs
- Cross-checks

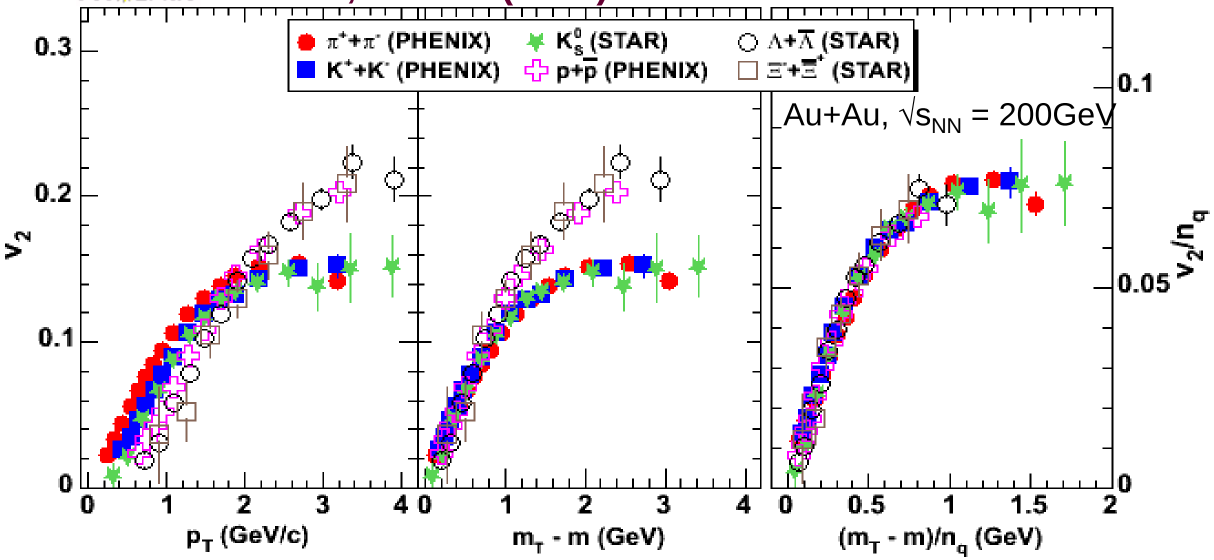
A Classic Result: Low p_T v_2

PRL 91, 182301 (2003)

- Large v_2 has been observed at RHIC
- v_2 at low p_T (~1.5 GeV/c) predicted by hydrodynamical models
- Results suggest early thermalization (~0.6 fm/c) and quark flow



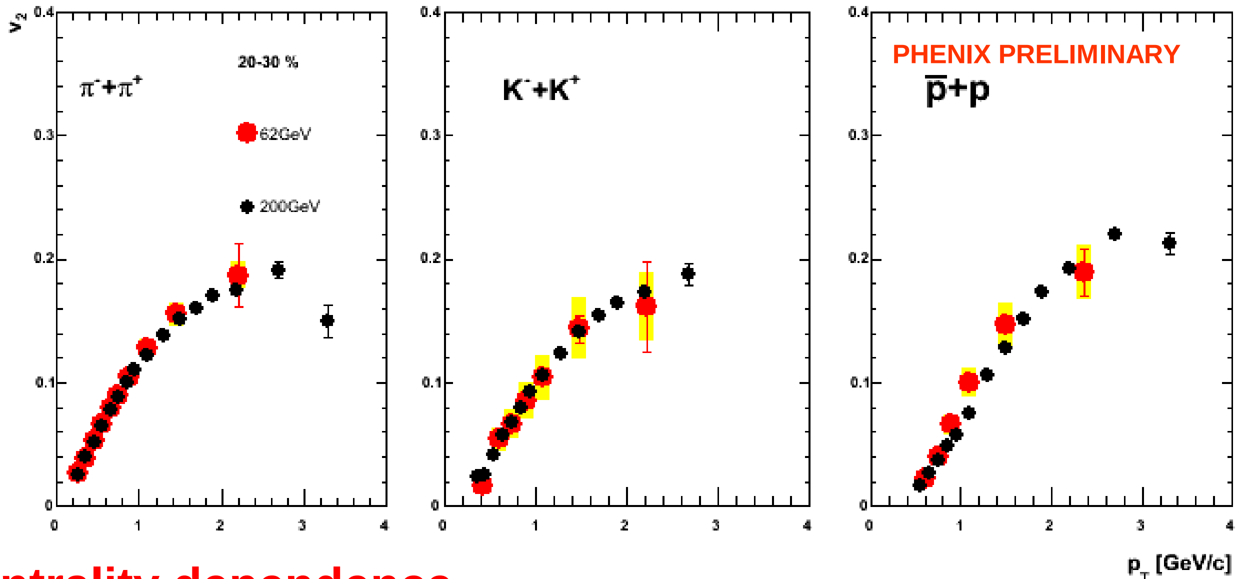
PRL. 98, 162301 (2007)



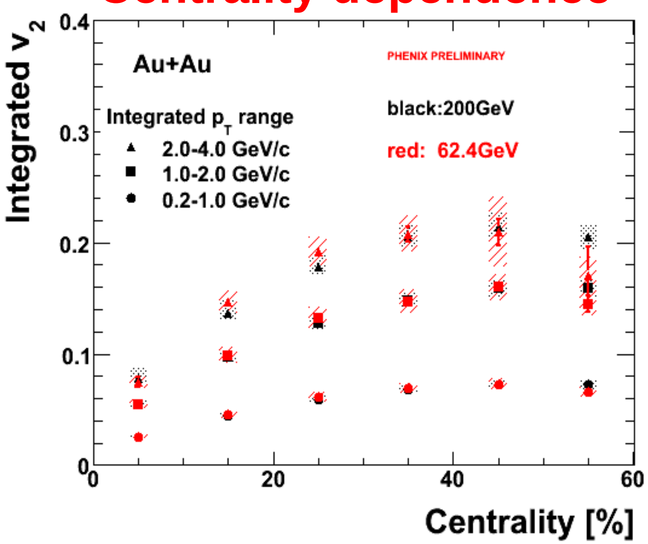
- KE_T/n_q scaling:
  - Up to ~1.0 GeV
  - Independent of species, system size, collision energy
- Doesn't seem to work at SPS energies
- Results suggest flow (at RHIC) develops at quark level

Energy dependence: AuAu 200 vs. 62.4

$v_2(p_T)$ for π/K/p 20-30% Centrality



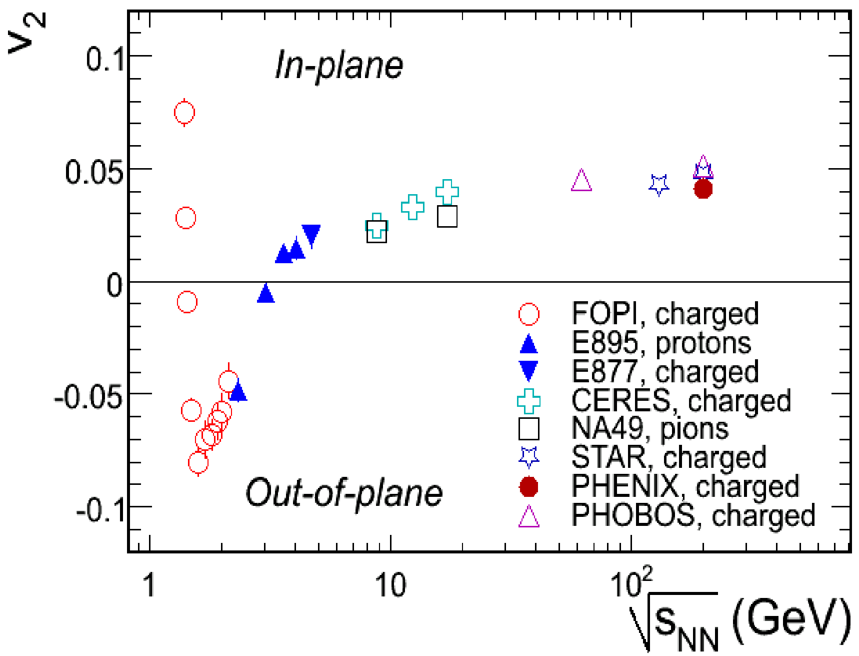
Centrality dependence



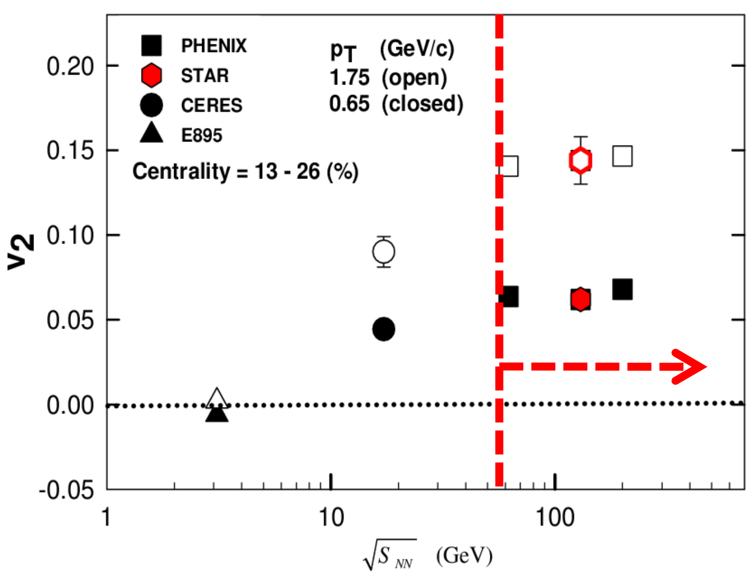
No significant difference between 200 and 62.4 GeV

Energy Dependence (II)

FOPI : Phys. Lett. B612, 713 (2005). E895 : Phys. Rev. Lett. 83, 1295 (1999)
CERES : Nucl. Phys. A698, 253c (2002). NA49 : Phys. Rev. C68, 034903 (2003)
STAR : Nucl. Phys. A715, 45c, (2003). PHENIX : Preliminary.
PHOBOS : Phys.Rev.Lett.98 242302 (2007)

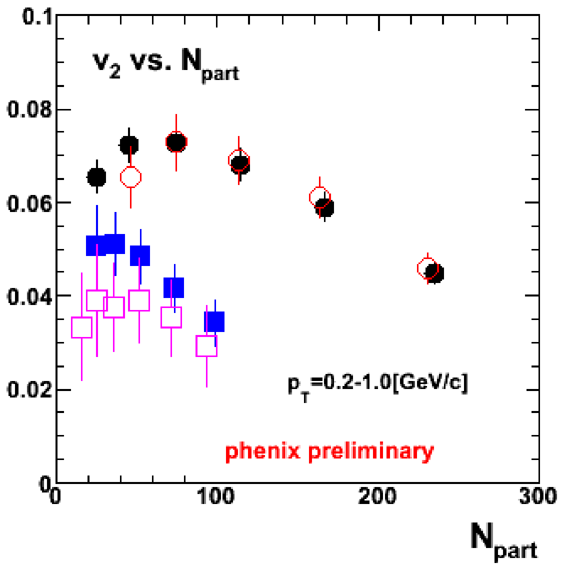


PRL94 232302 (2005)

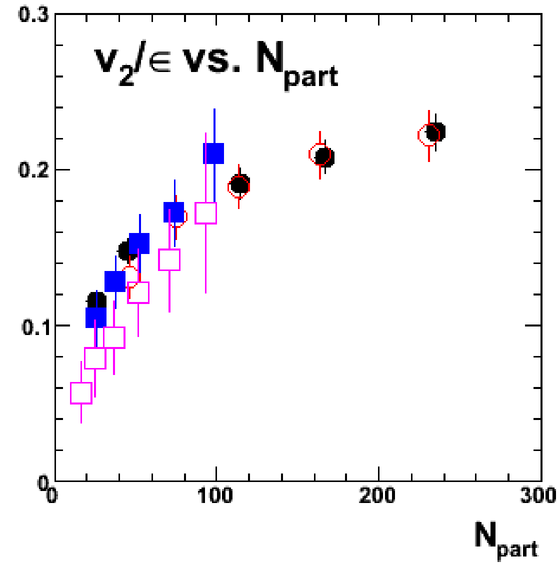


- v_2 appears to saturate above 62.4
  - Evidence for matter reaching thermal equilibrium at RHIC…

System size dependence: AuAu vs. CuCu



Scale by eccentricity



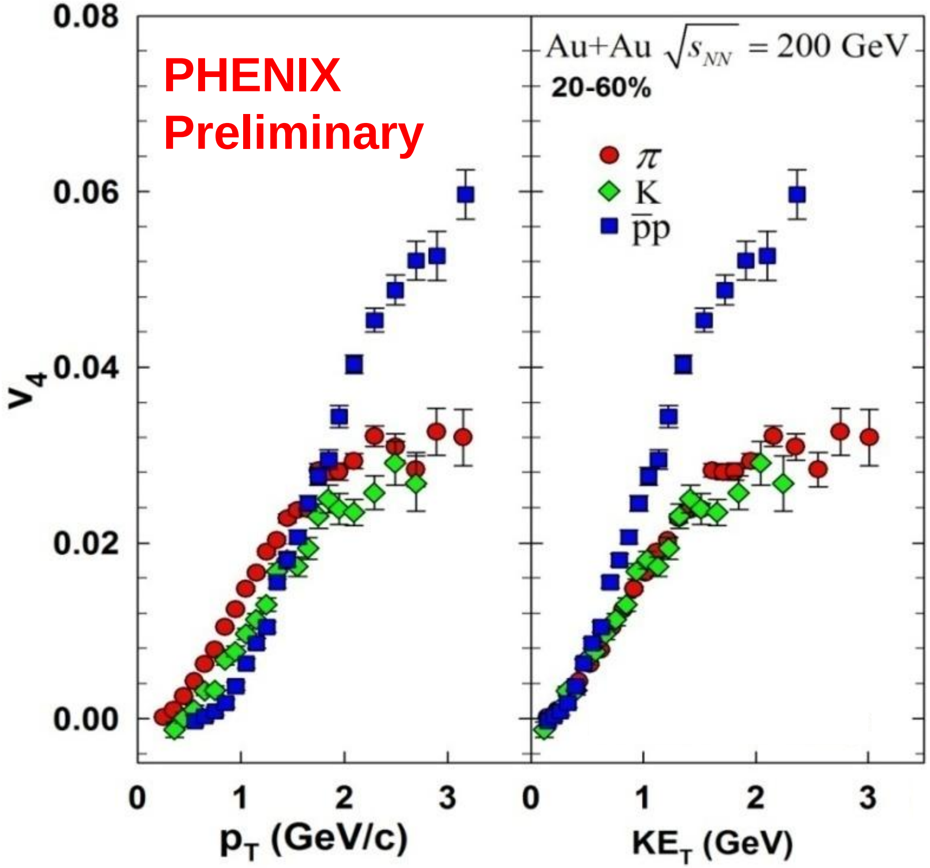
$0.2<p_T<1.0$ [GeV/c]

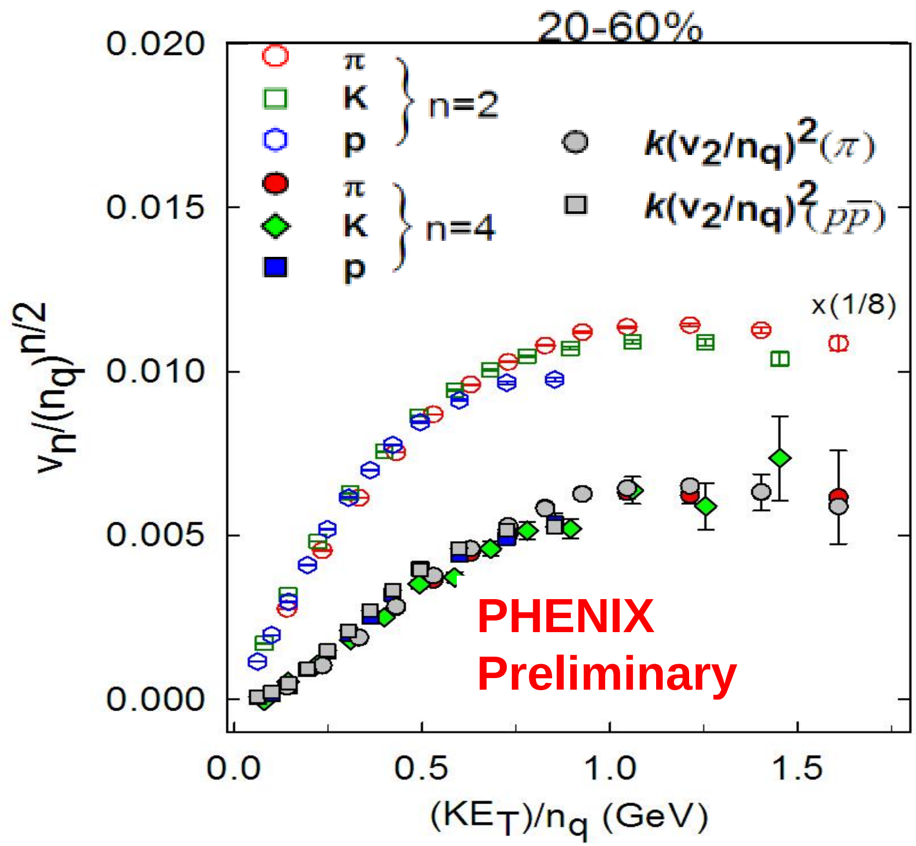
- ● AuAu 200GeV
- ○ AuAu 62.4GeV
- ■ CuCu 200GeV
- □ CuCu 62.4GeV

- Eccentricity scaling: further evidence of early thermalization

PHENIX Also Measures v_4

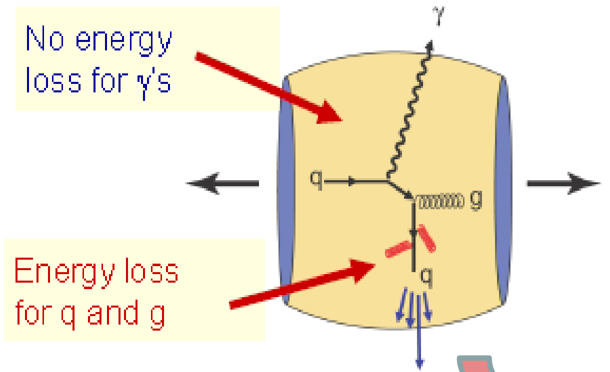
QM09, A. Taranenko



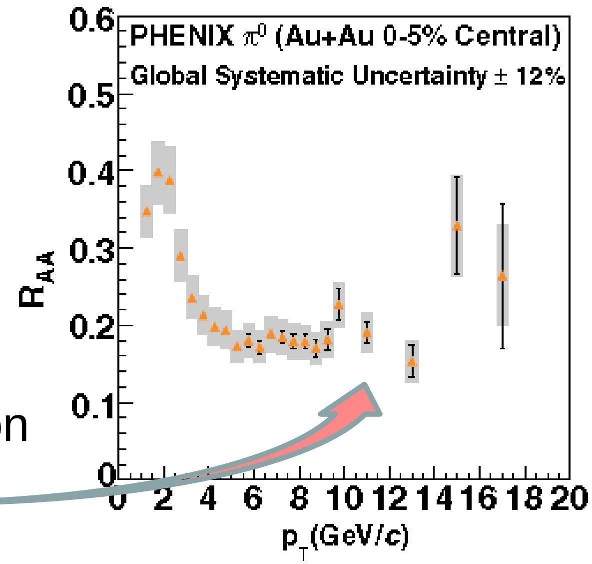


- Quark/KE_T scaling works for v_4 as well
- $v_4 \propto v_2^2$ independent of the particle species

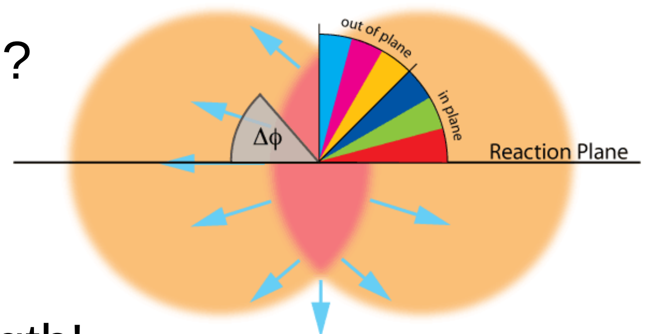
High-p_T: Domain of hard-scattering



High-p_T suppression

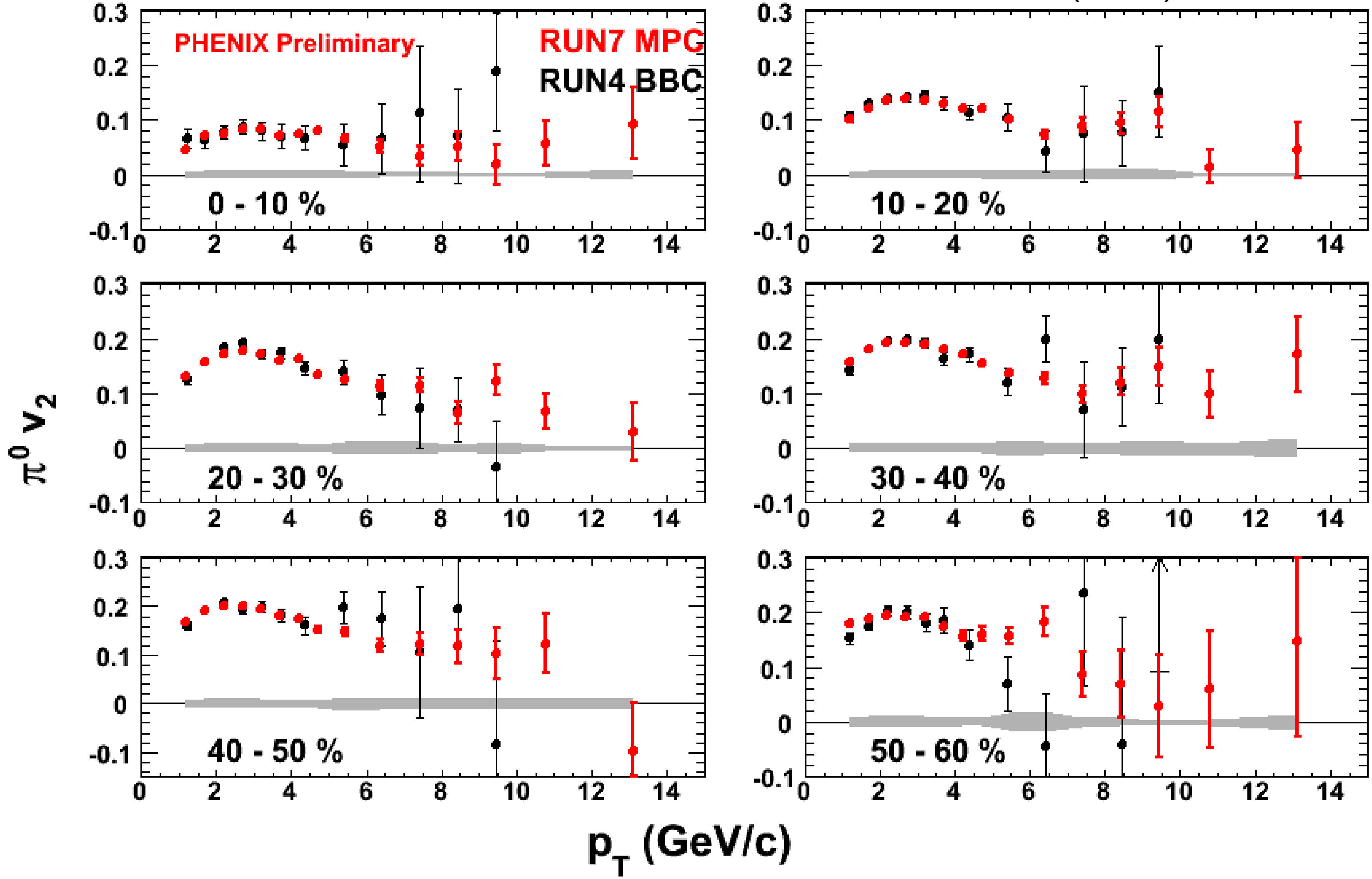


- Jets are quenched
  - But what are the details of the quenching?
- RP to the "rescue"
  - Centrality studies help to constrain the geometry
  - Angle with respect to RP: fix the path length!



High-p_T π^0 v_2

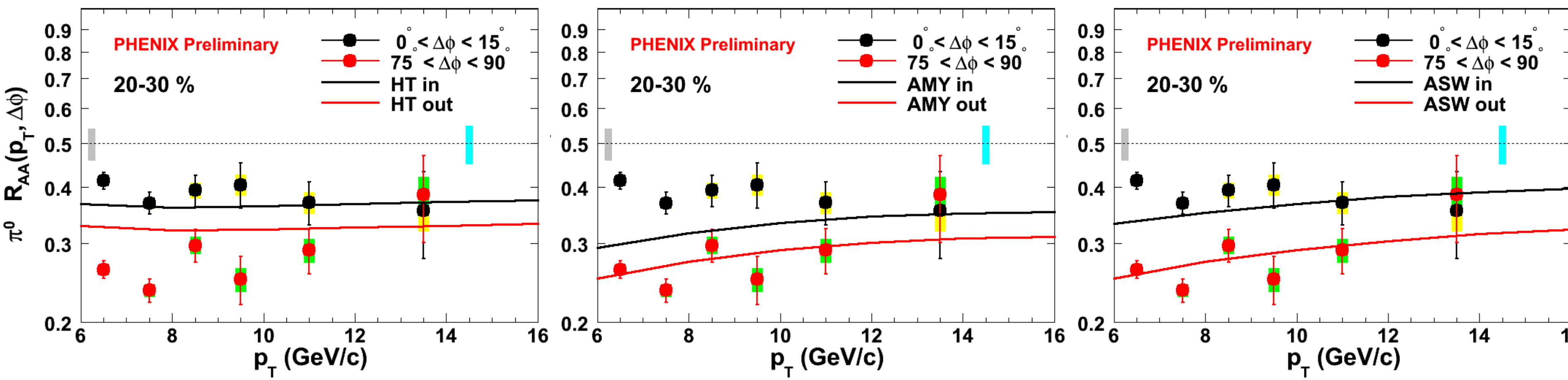
(Run-4) PRC 80 054907 (2009)



- Run-7 has increased p_T reach to 14 GeV/c
- Stronger evidence for non-zero v_2 at high p_T

$R_{AA}(\Delta\phi)$ compared with models

Run-7 Au+Au 200 GeV 20-30%

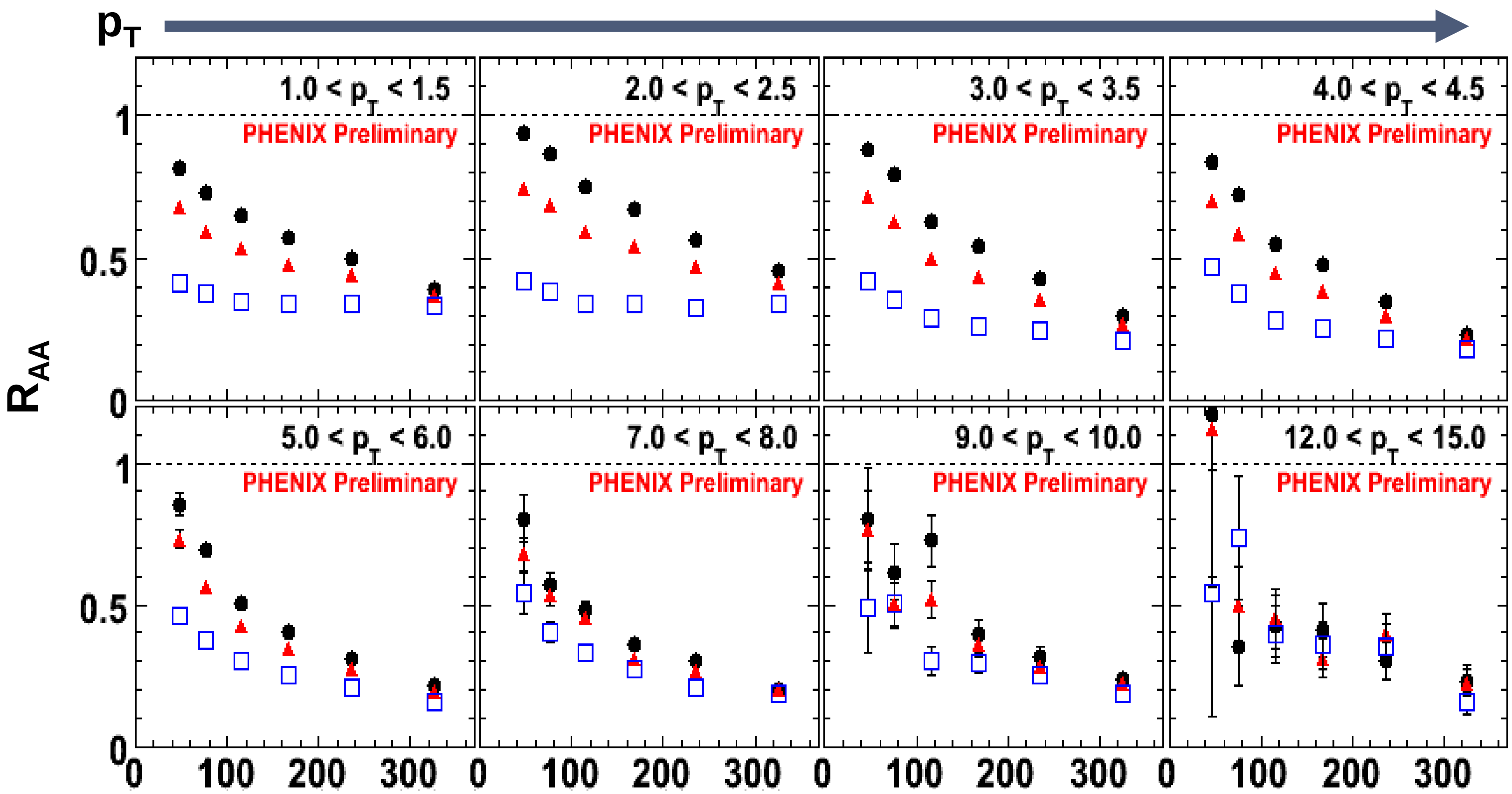


Model calculations from S.Bass et al. PRC79 024901 (2009)

$\hat{q}(\vec{r},\tau)$ scales as	ASW $\hat{q}_0$	HT $\hat{q}_0$	AMY $\hat{q}_0$
$T(\vec{r},\tau)$	10 $\mathrm{GeV}^2/\mathrm{fm}$	2.3 $\mathrm{GeV}^2/\mathrm{fm}$	4.1 $\mathrm{GeV}^2/\mathrm{fm}$
$\epsilon^{3/4}(\vec{r},\tau)$	18.5 $\mathrm{GeV}^2/\mathrm{fm}$	4.5 $\mathrm{GeV}^2/\mathrm{fm}$	
$s(\vec{r},\tau)$		4.3 $\mathrm{GeV}^2/\mathrm{fm}$	

- In-plane: flat with p_T
  - Data favor ASW and HT
- Out-of-plane: smaller energy loss with increasing p_T
  - Data favor ASW and AMY

$R_{AA}(N_{part})$ in- vs. out-of-plane

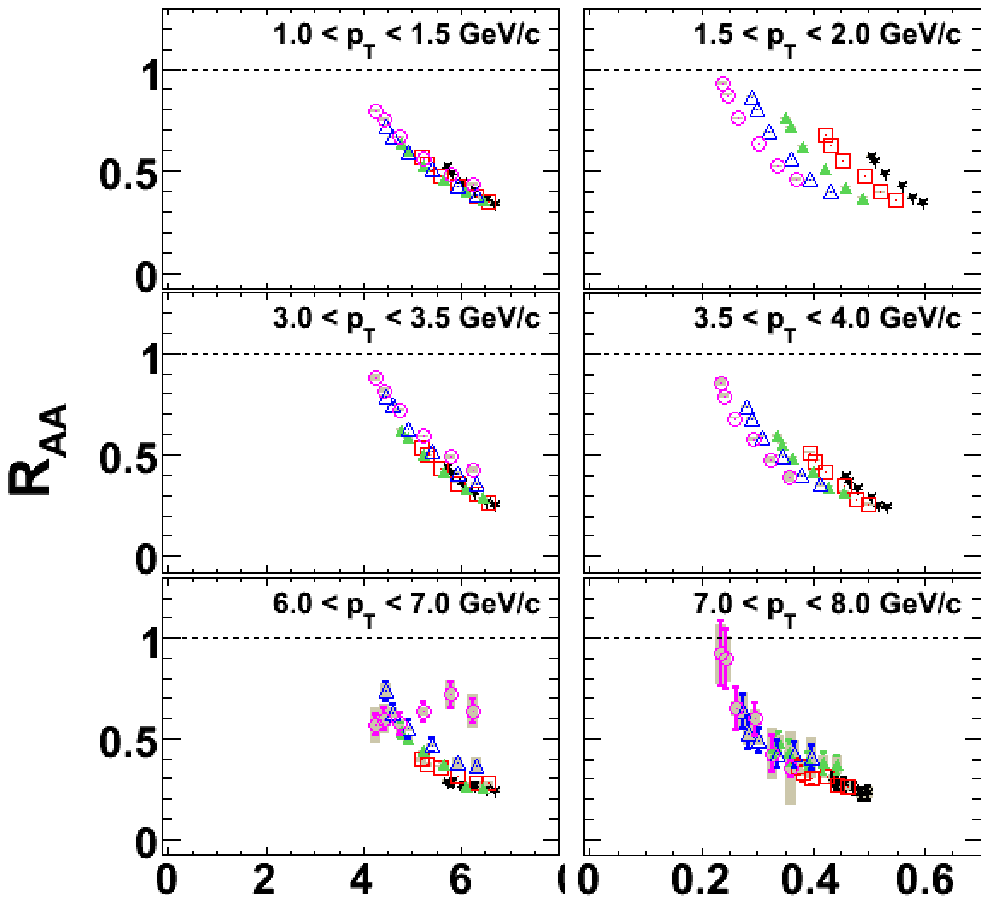


- in-plane
- intermediate
- out-of-plane

- Out-of-plane: (Low-p_T) has little or no N_{part} dependence
- In-plane: rapidly changing with N_{part}
- Clear separation of geometries in the two directions

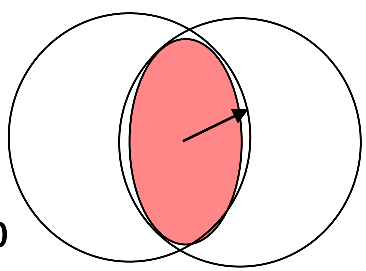
R_{AA} vs. Path Length

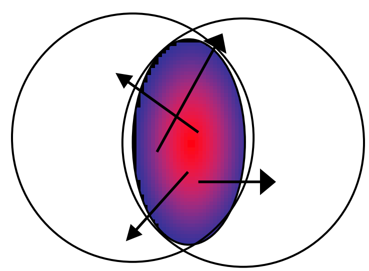
PRC 80 054907 (2009)



- Centrality and angle used to estimate path length
- Several approaches
  - Hard spheres
  - Glauber ellipse
  - Effective path length
  - Eff. Path, normalized
- Consistent with geometry dominating at low p_T and E loss at high p_T

Hard sphere overlap

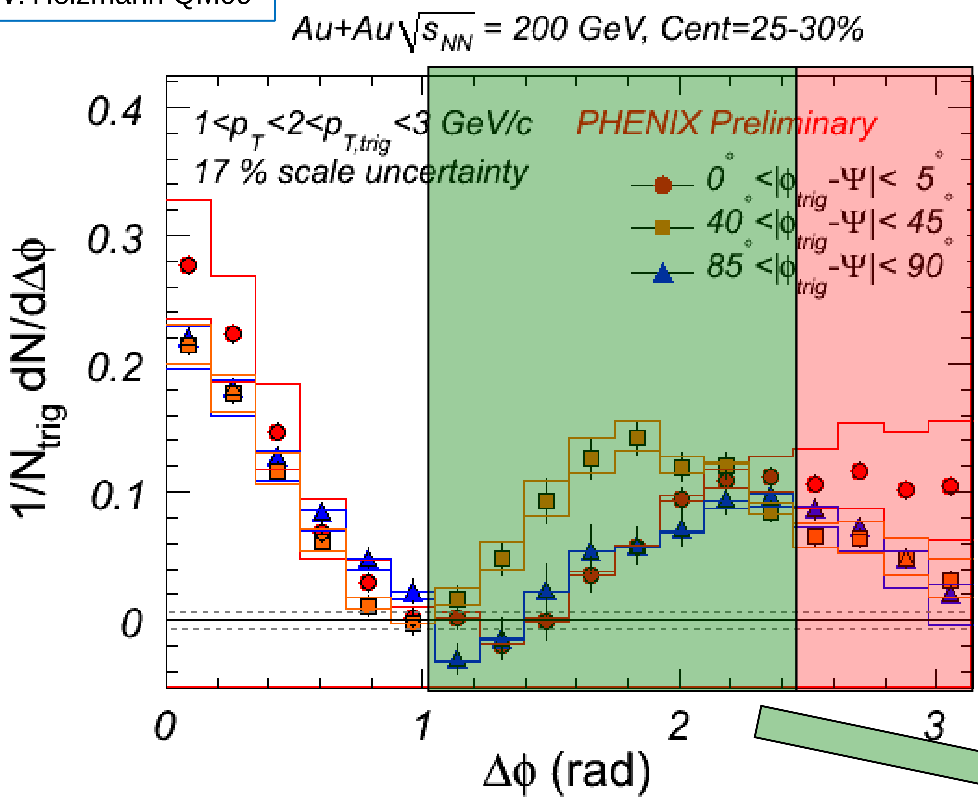


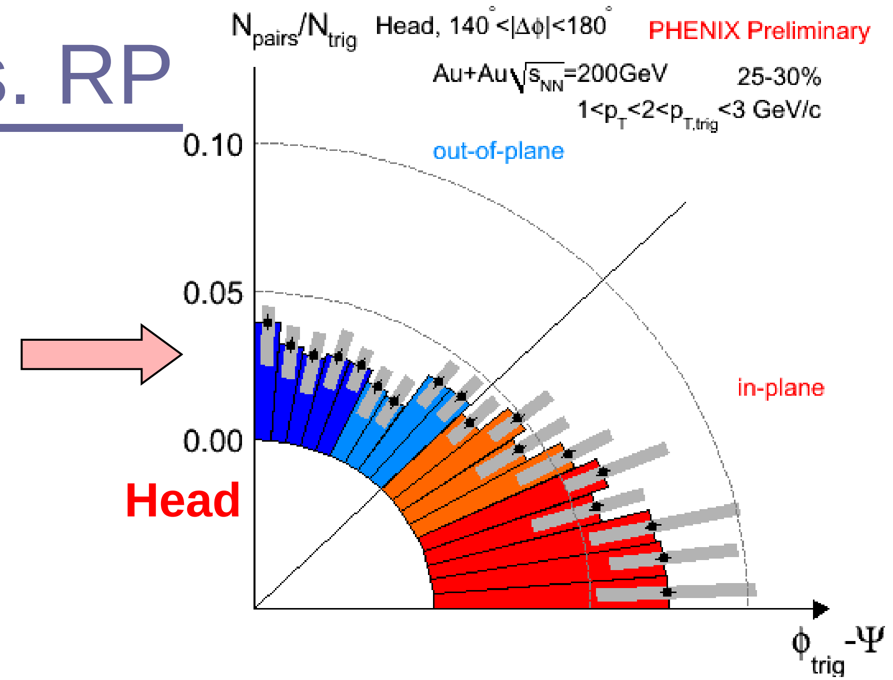


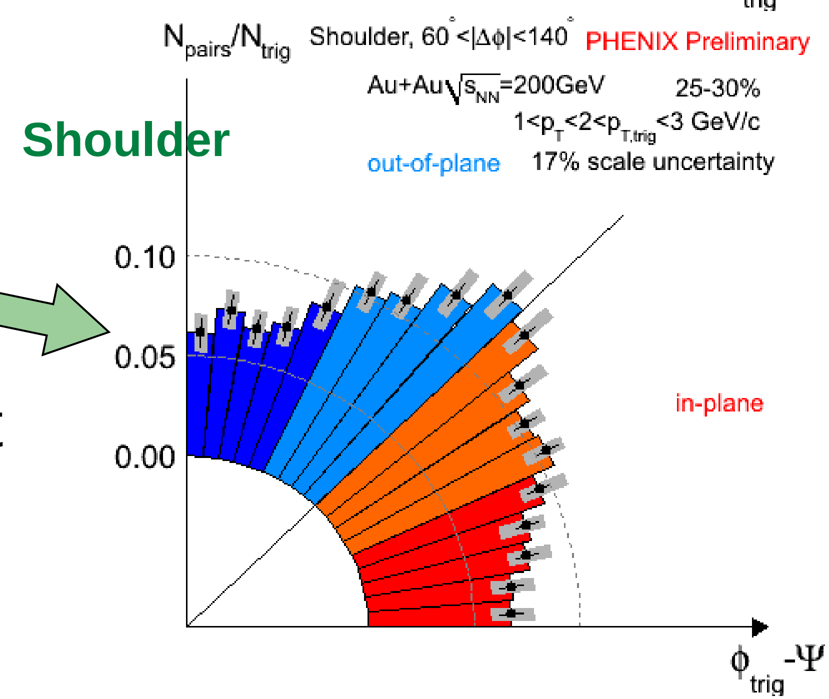
MC-sampled, weighted pathlength

Azimuthal Correlations vs. RP

W. Holzmann QM09

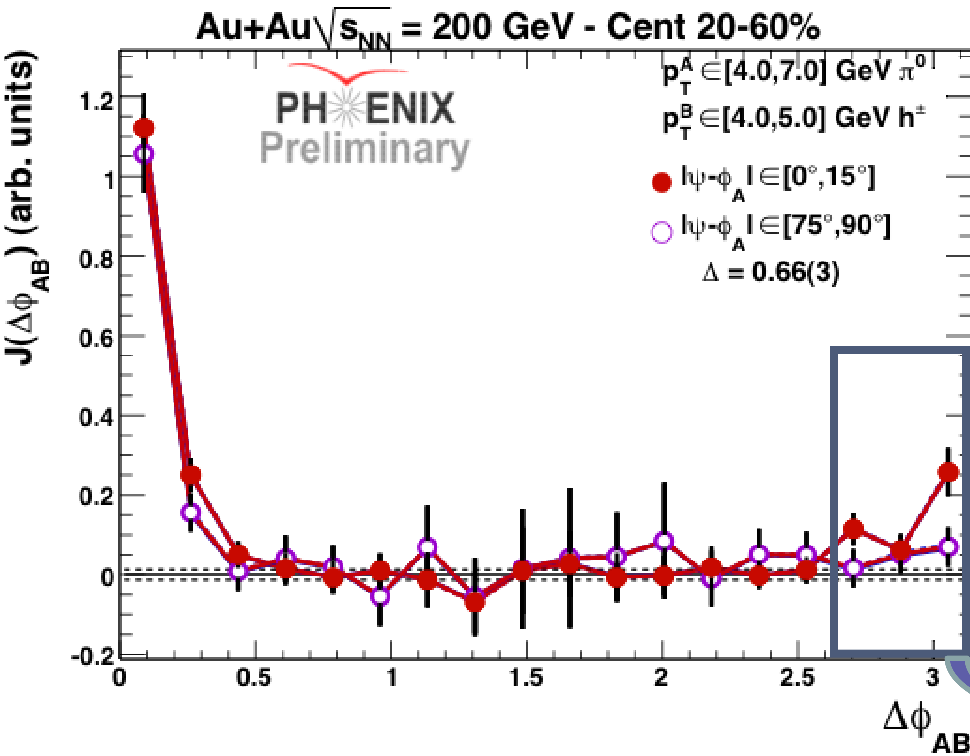


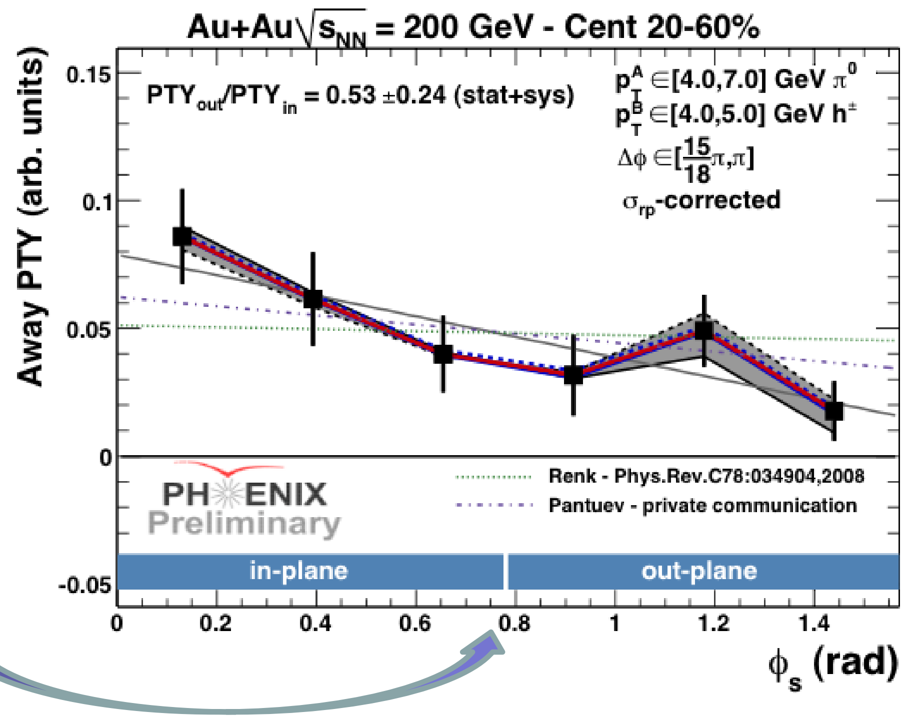


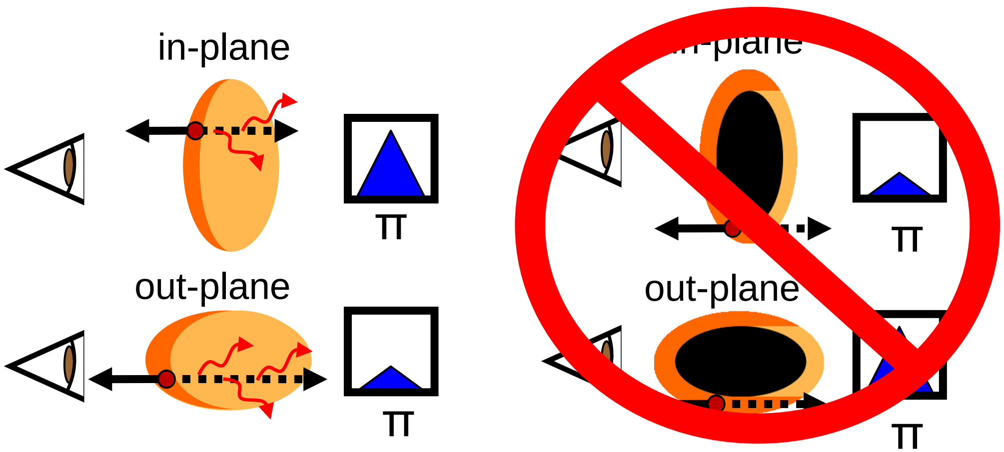


- Head region clearly shows effect of energy loss from path length
- Situation more complex in the shoulder region

Away-side at high(er)-p_T vs. RP

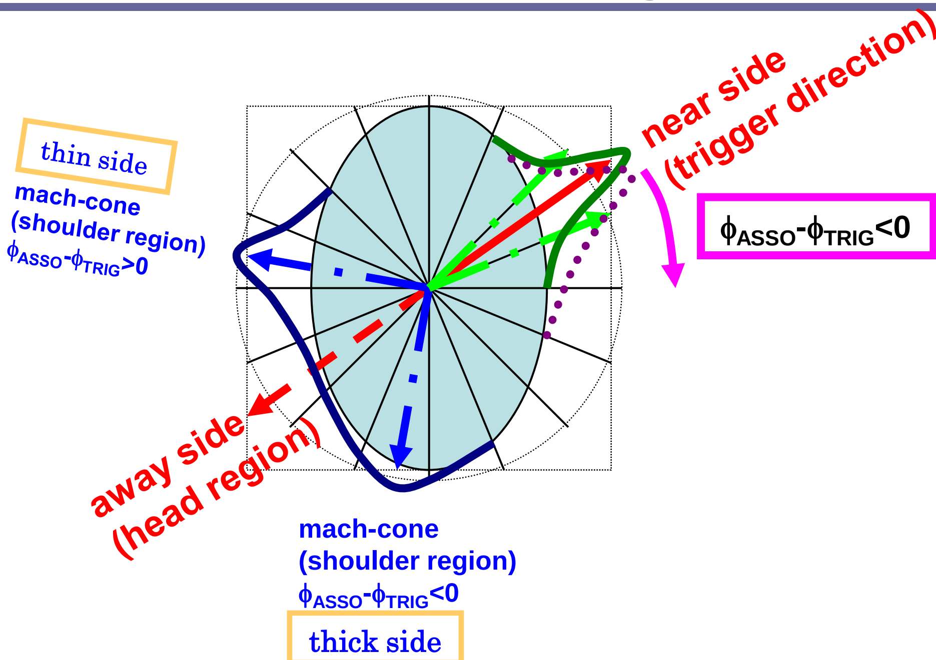




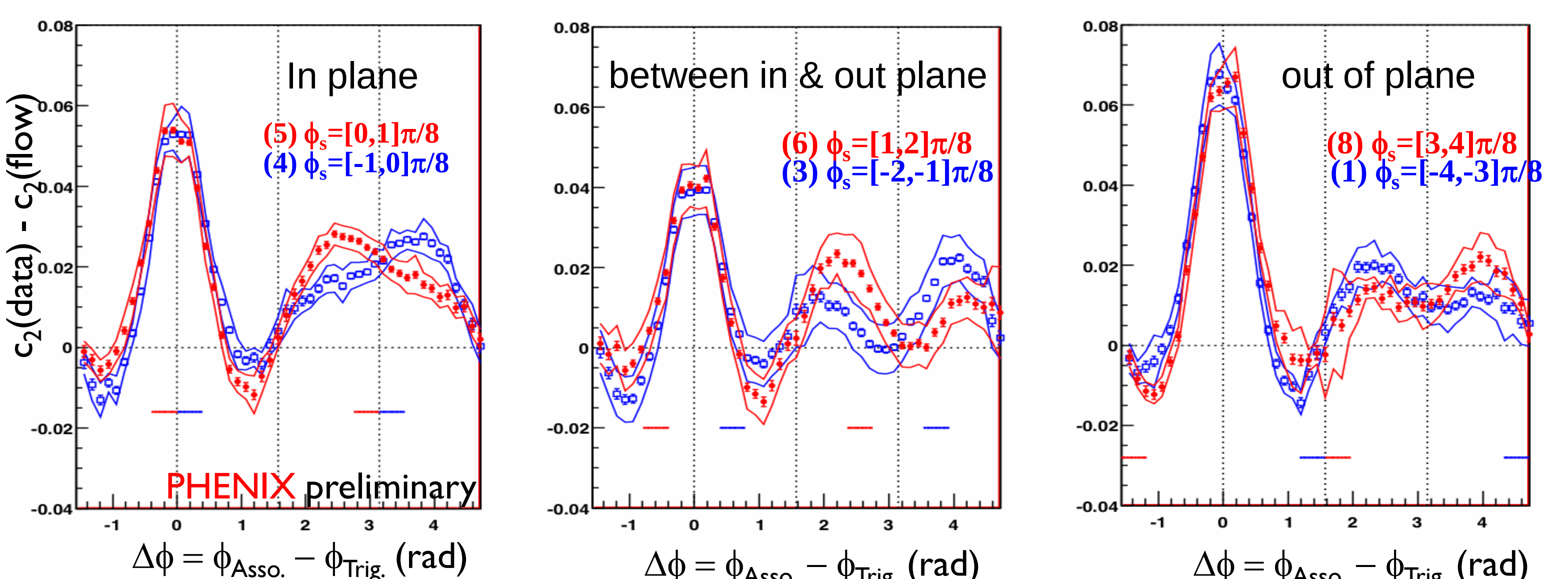


In- to out-of-plane falling per-trigger-yields favor a penetrating production picture

Near-/Far-side Asymmetries



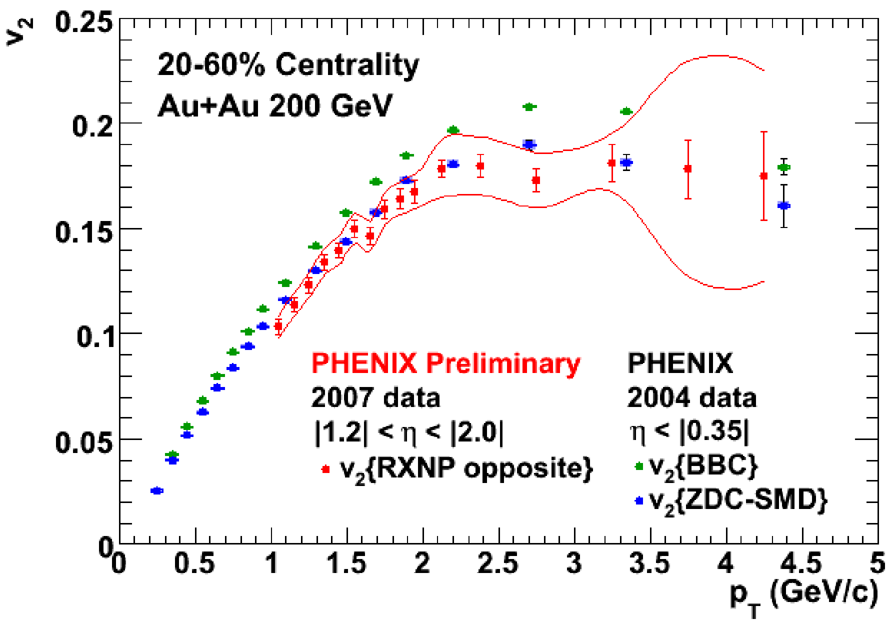
For a fixed trigger particle angle, the associated particles emitted left or right w.r.t. trigger direction will see the different thickness of the almond:
Probe the geometry of the collision

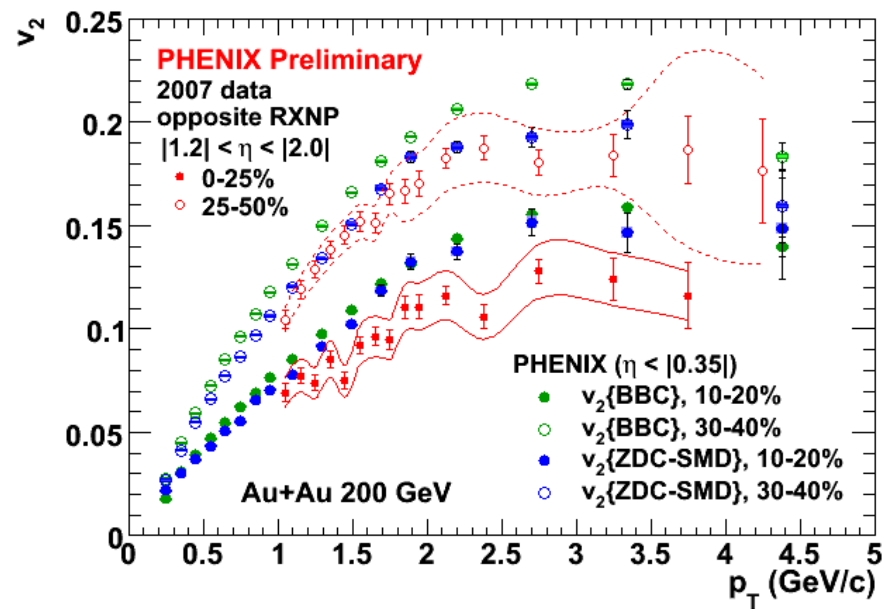


- Run-7
- 20-50%
- Trig: 2-4 GeV/c
- Asso: 1-2 GeV/c

S. Esumi QM09

Forward hadron v_2

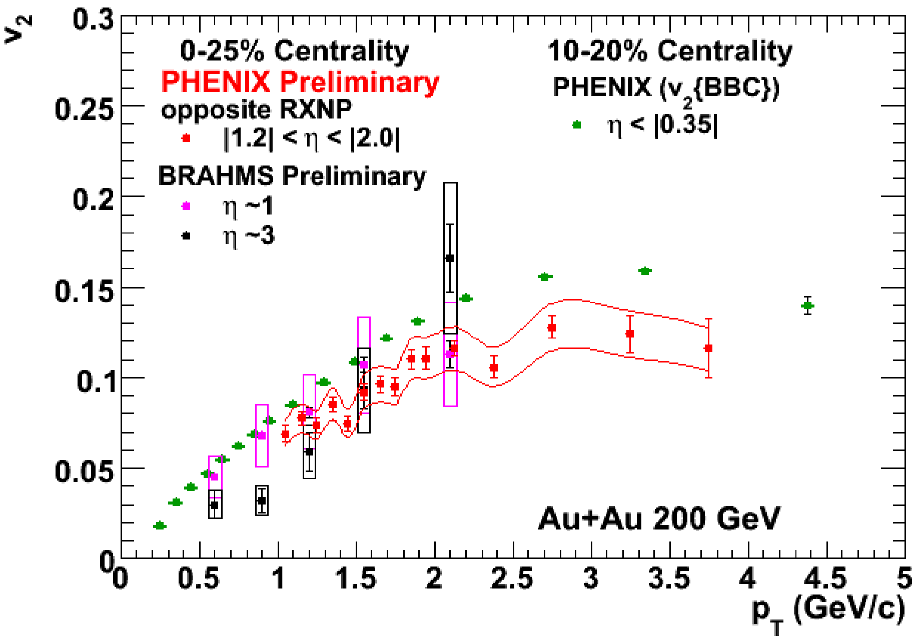




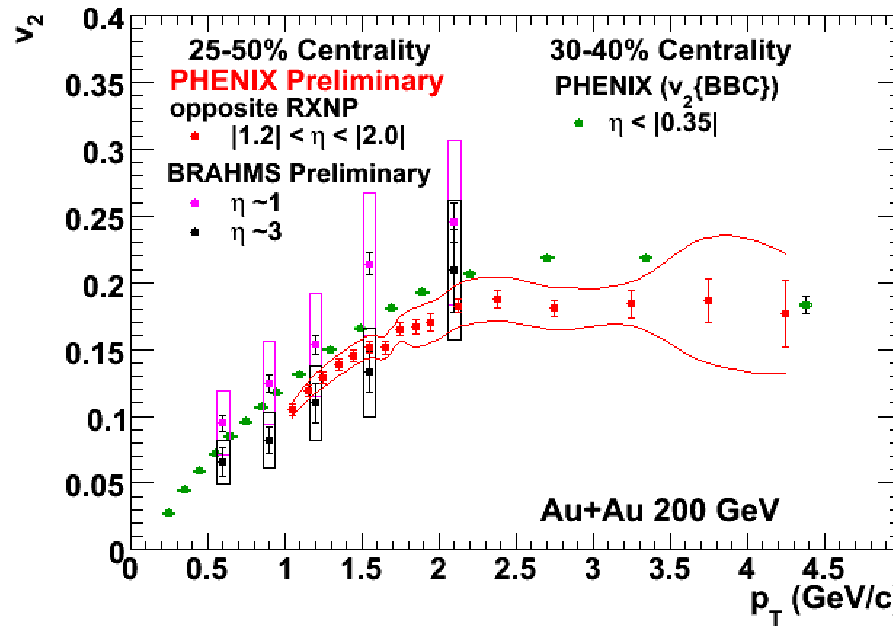
- Syst uncertainty band includes:
  - Reaction plane resolution
  - Background estimation
  - Reaction plane angle used
- Similar results between mid and forward rapidity
- Mid-central collisions: exhibit lower v_2 at forward rapidity

Forward hadron v_2: η dependence

Compare:
0-25% Forward vs. 10-20% mid



Compare:
25-50% Forward vs. 30-40% mid

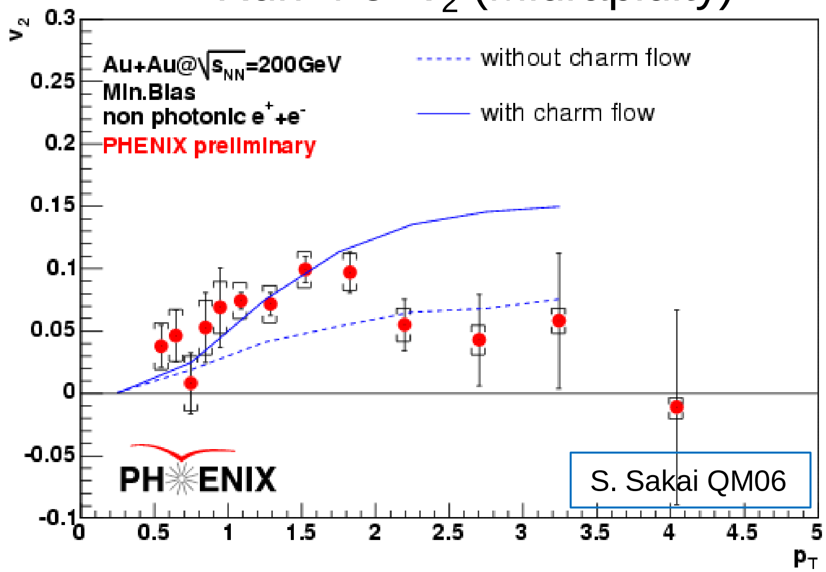


Data consistent with a falling signal in the forward directions

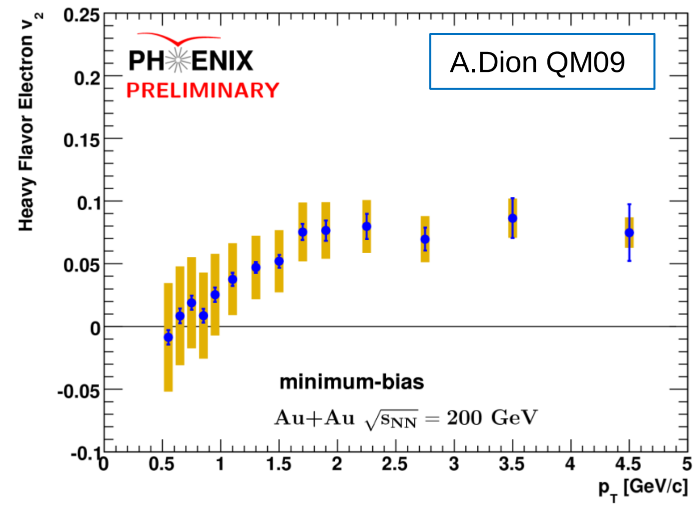
- Though uncertainties are sizeable

Heavy flavor and J/ψ

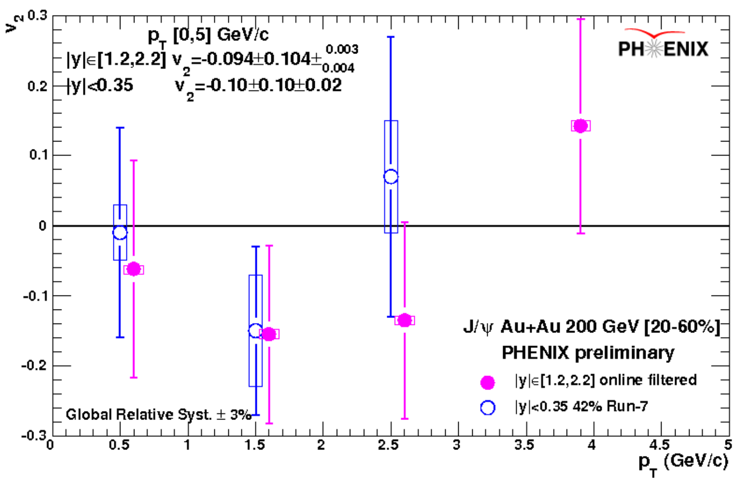
Run-4 $e^{\pm}$ v_2 (Midrapidity)



Run-7 $e^{\pm}$ v_2 (Midrapidity)



Run-7 J/ψ v_2 (Mid and forward)



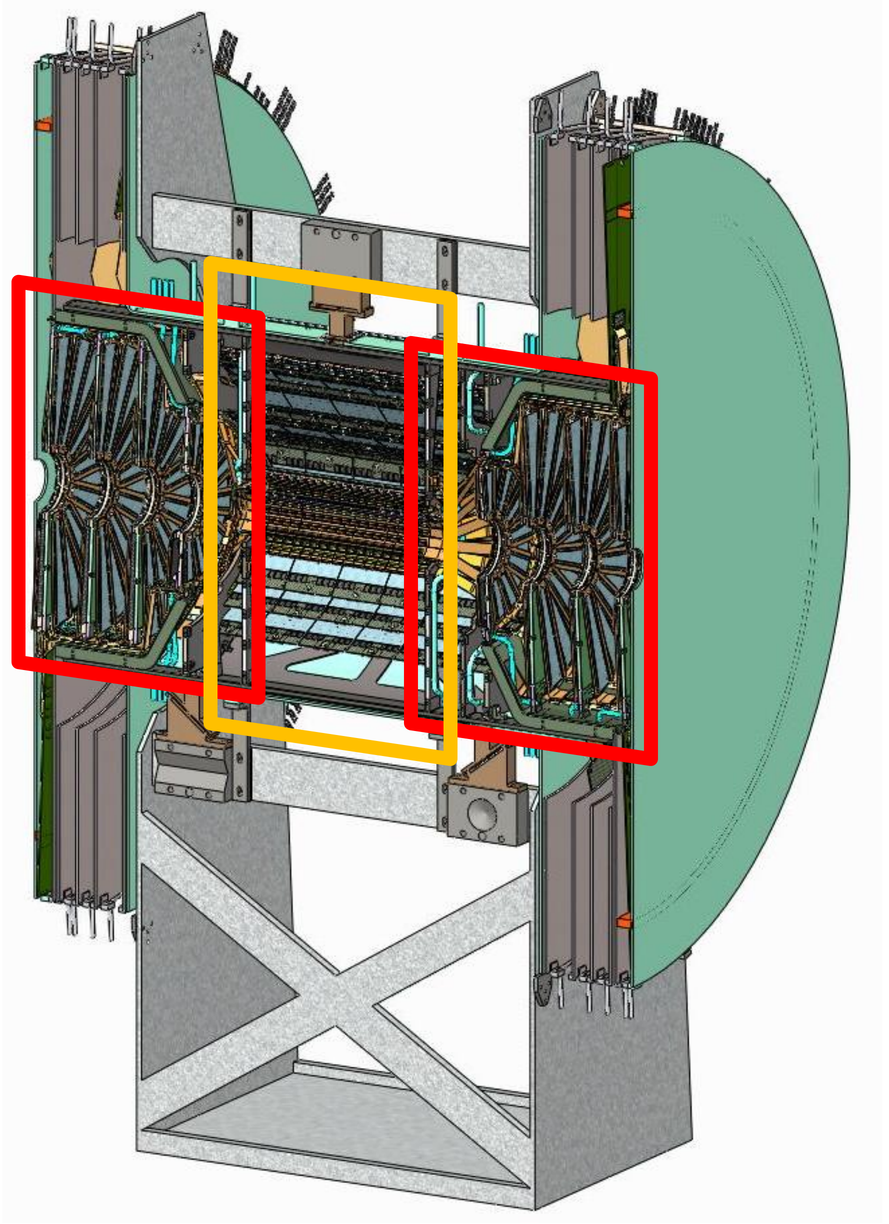
- Low p_T electron v_2 favor models with charm quark flow
- Limited statistics prevent measuring J/ψ flow definitively
- B-meson decay important above 2.5 GeV/c
  - Motivates need for b/c separation in upgrades

The Future in PHENIX RP Studies

PHENIX

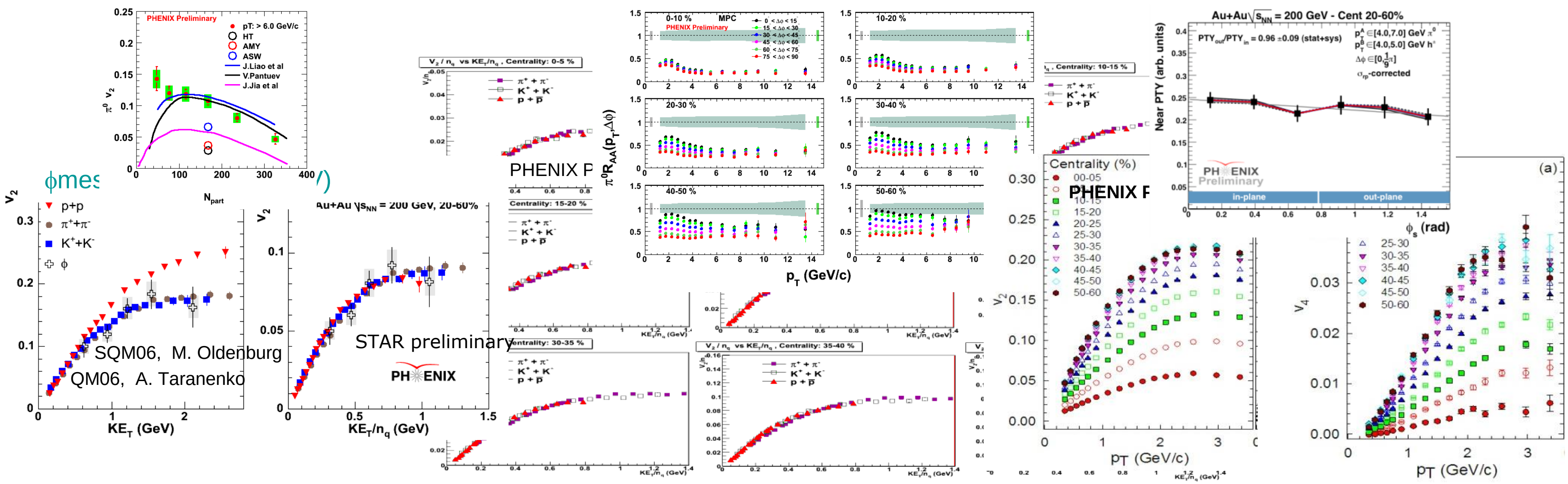
Vertex Detector (VTX) and Forward Vertex Detector (FVTX):

- Four Si tracking layers per endcap (FVTX) and barrel (VTX)
- FVTX in same region as RXNP
  - Matches muon arms
  - $1.2 < |\eta| < 2.4$
- Goals:
  - Improved tracking in muon (FVTX) and central (VTX) arms
  - b/c separation
  - Potential RP measurement (FVTX)



Summary

- The reaction plane is a powerful tool, providing access to a wide variety of probes and measurements for heavy-ion collisions
- PHENIX has strong reaction plane capabilities, and has used them in a variety of analyses
  - Elliptic flow (high, low p_T) and v_4
  - Forward and heavy flavor flow
  - Probe parton energy loss as function of geometry
- Unfortunately not enough time to cover every possible topic:



Backup slides

Reaction Plane and Resolution

Event plane method:

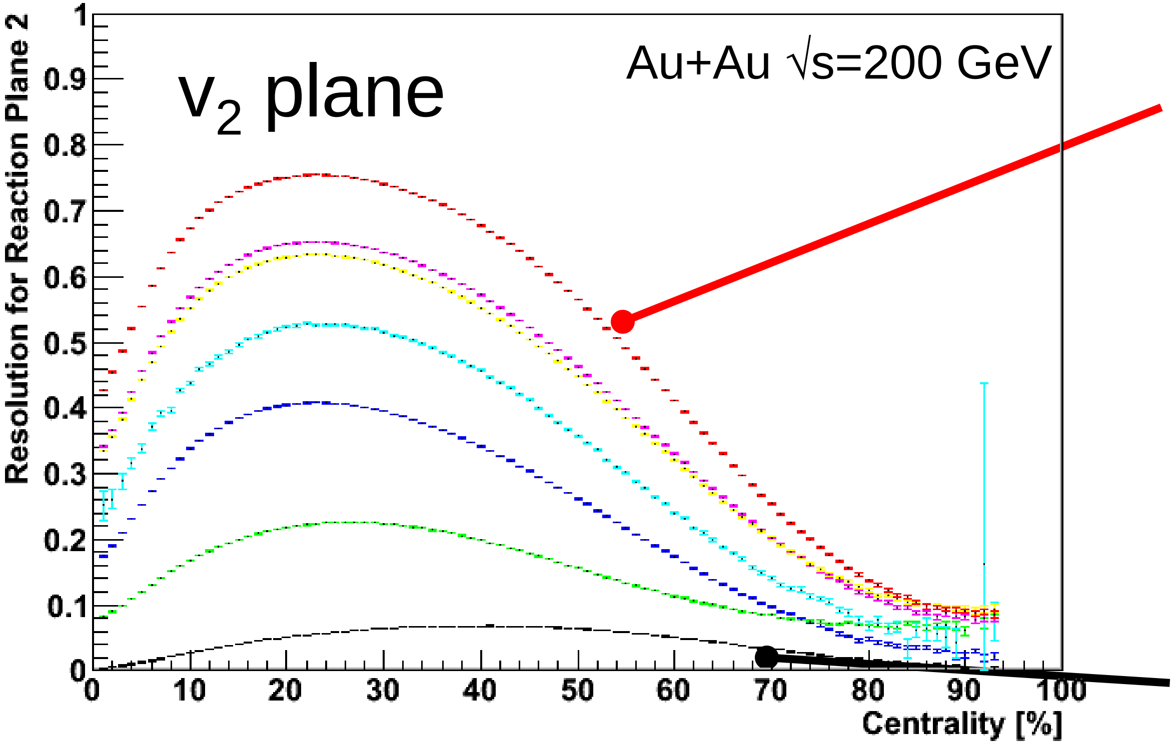
$$n\Psi_n = \tan^{-1}\left(\frac{\sum_i^M w_i \cos n\phi_i}{\sum_i^M w_i \sin n\phi_i}\right)$$

Subevent method is used to estimate resolution:

$$\sigma_{RP} = \sqrt{\left\langle \cos\left[n\left(\psi_n^a - \psi_n^b\right)\right]\right\rangle}$$

Resolution is used to correct observed modulation:

$$v_2 = v_2^{raw} / \sigma_{RP}$$



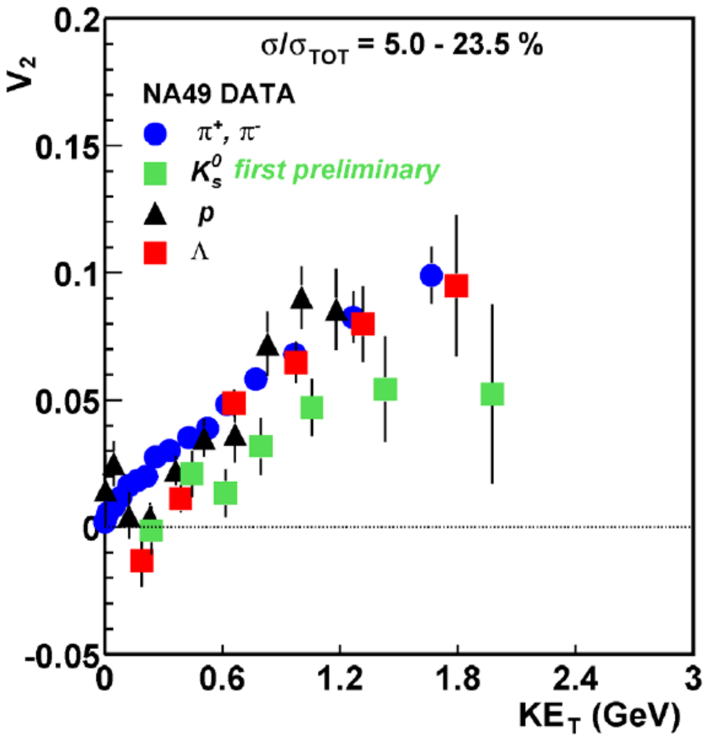
- RXNP: $1.0<|\eta|<2.8$
- RXNPin: $1.5<|\eta|<2.8$
- RXNPout: $1.0<|\eta|<1.5$
- MPC: $3.0<|\eta|<4.0$
- BBC: $3.0<|\eta|<4.0$
- CNT: $0.0<|\eta|<0.35$
- SMD: $|\eta|>6$

quark number scaling at SPS

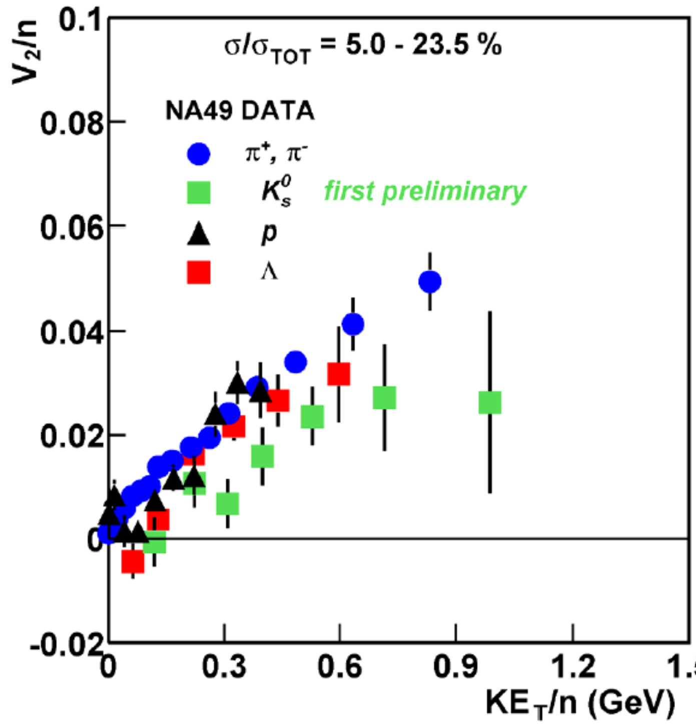
PHENIX

v_2 of p, π, Λ - C. Alt et al (NA49 collaboration) nucl-ex/0606026 submitted to PRL
v_2 of K^0 (preliminary) - G. Stefanek for NA49 collaboration (nucl-ex/0611003)

Pb+Pb at 17.2 GeV, NA49



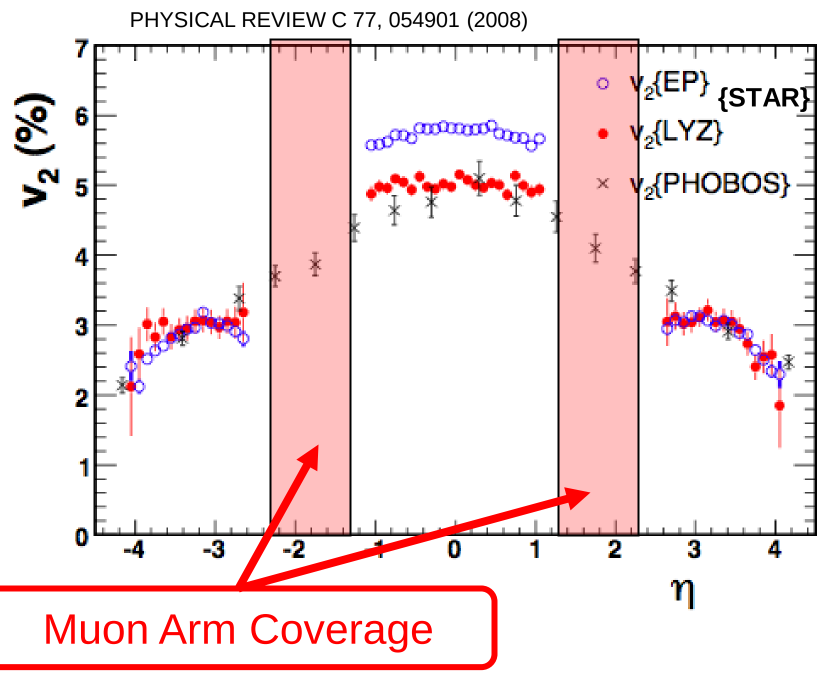
A. Tranenko's talk at QM06



- Quark number + K_{ET} scaling doesn't seem to work out at SPS.
- No flow at quark level due to nonexistence of QGP ?

Flow at Forward Rapidities

PHENIX

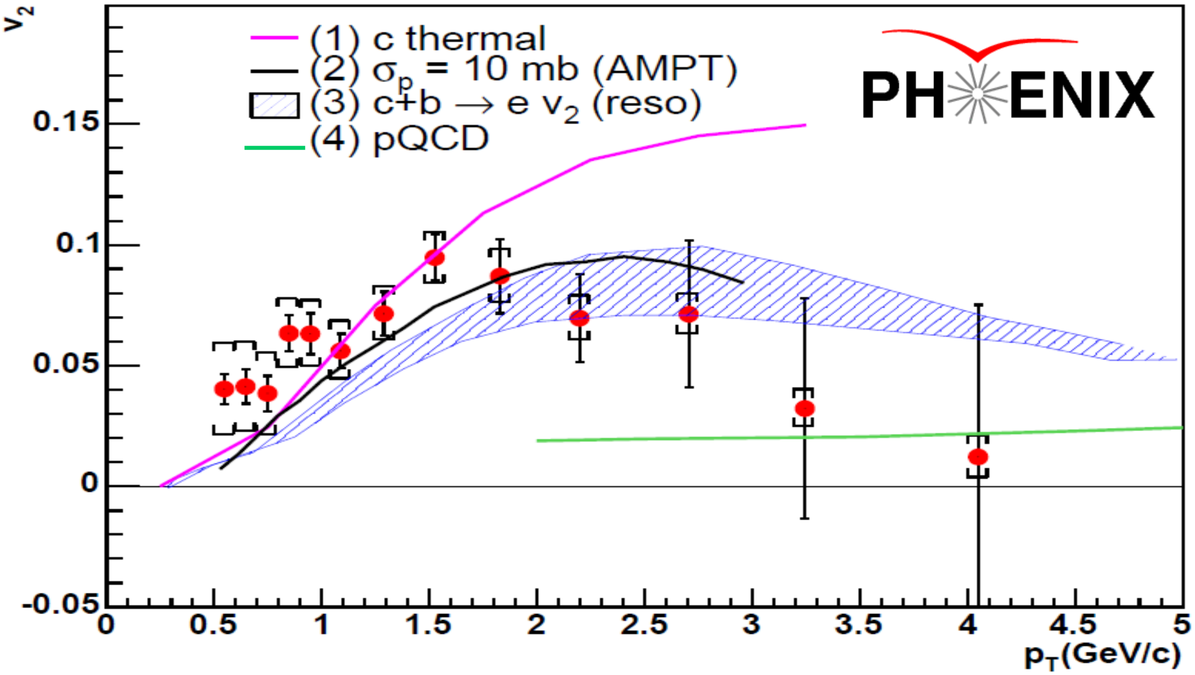


- PHENIX forward measurements use the Muon Arms
- Unique measurement:
  - Covers 1.2<|η|<2.4
  - Provides p_T
- Aid in understanding η dependence of v_2

Have to be careful! Measurement of reaction plane for Muon Arms:

- RXNP and Muon Arms overlap in η → autocorrelations!
- Use RP from opposite arm:
  - South Muon Arm -> North RXNP
  - North Muon Arm -> South RXNP

Electron v_2 – Compare with models



(1) Charm quark thermal + flow [Phys.Lett. B595 202-208]

(2) large cross section ; ~10 mb [PRC72,024906]

(3) Resonance state of D & B in sQGP [PRC73,034913]

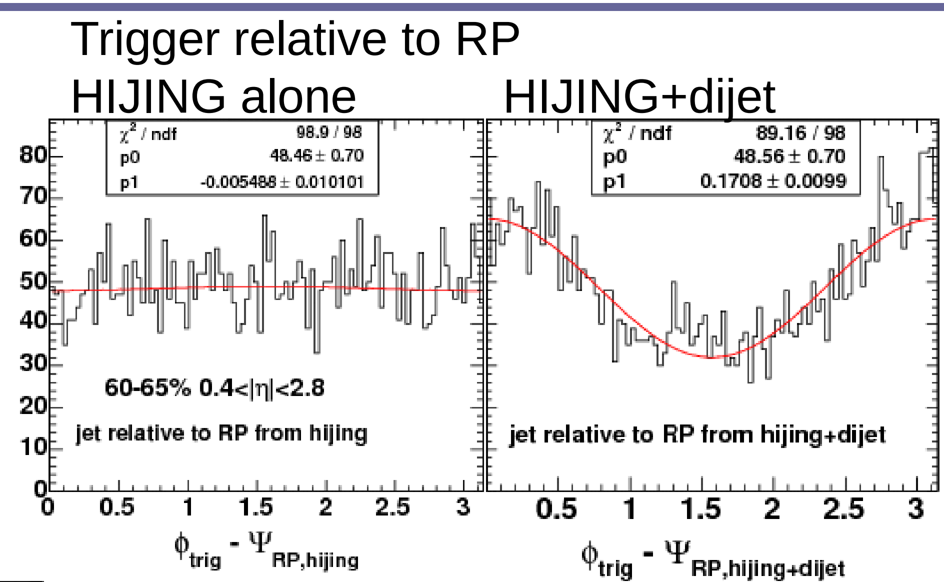
work

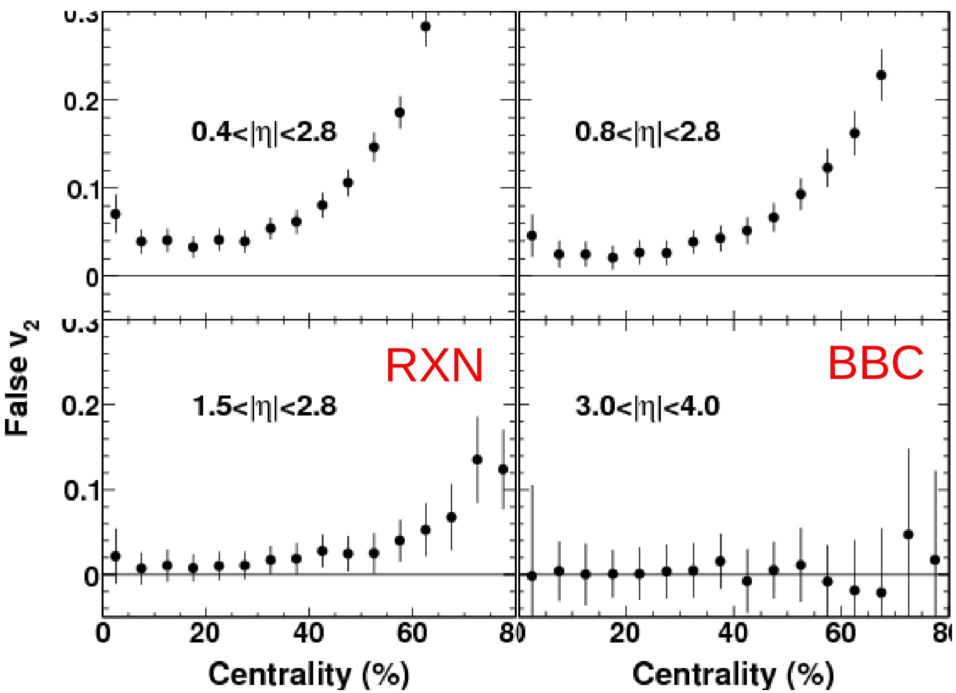
(4) pQCD [PRB637,362] --- fail

=> Charm quark strongly coupled to the matter

Non-flow effects?

- Embed pythia events in HIJING
- Implement v_2 modulation by weighting HIJING particles with $v_2(\text{cent},p_T)$





- Measure “fake” v_2 of jets
- Effect varies as function of η where v_2 is measured

arXiv:0801.4545v1 [nucl-ex]