PHENIX Results on Jet Correlations versus Reaction Plane

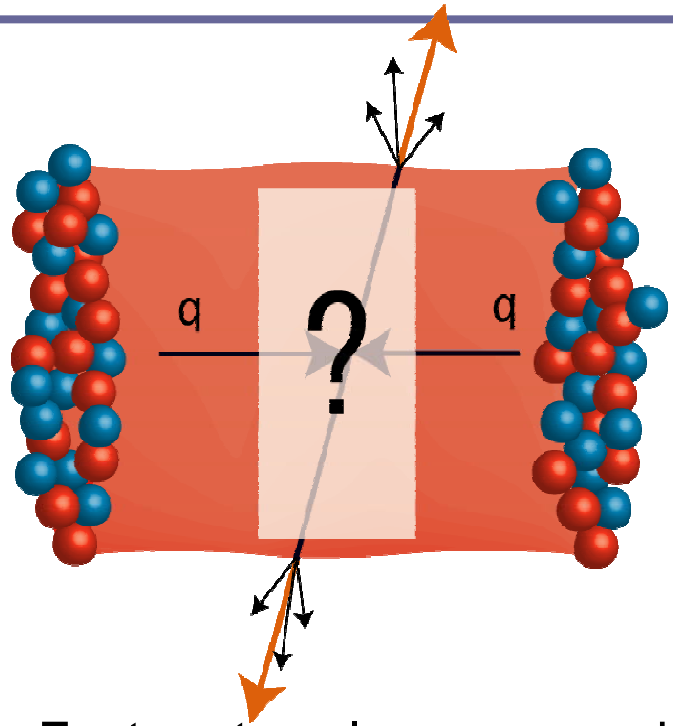
David Winter
24th Winter Workshop on Nuclear Dynamics
South Padre Island, TX
8 April 2008

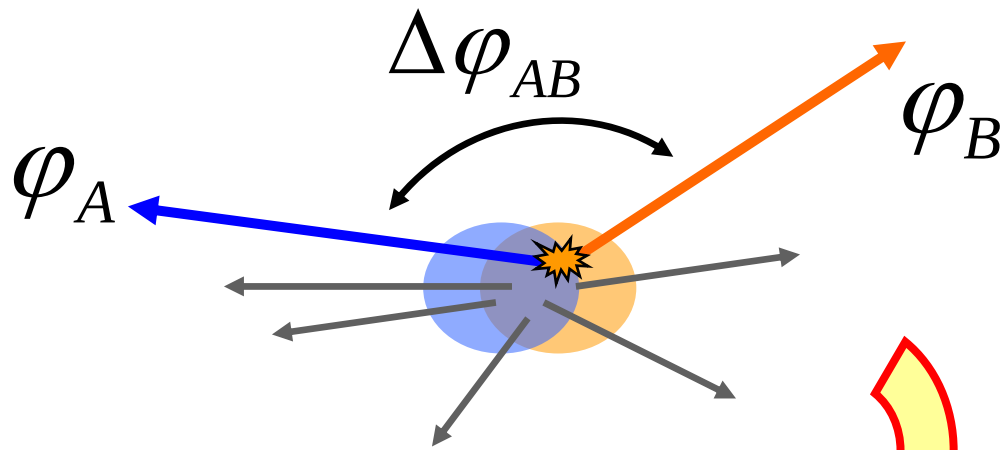
David L. Winter
for the PHENIX Collaboration
Columbia University
in the City of New York

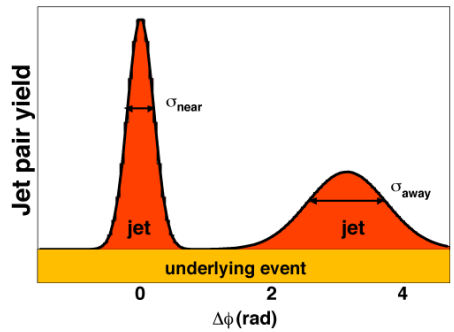
Outline

- Motivation
- Background/PHENIX
- Results
- Future/Summary

Jet Correlations and the Medium



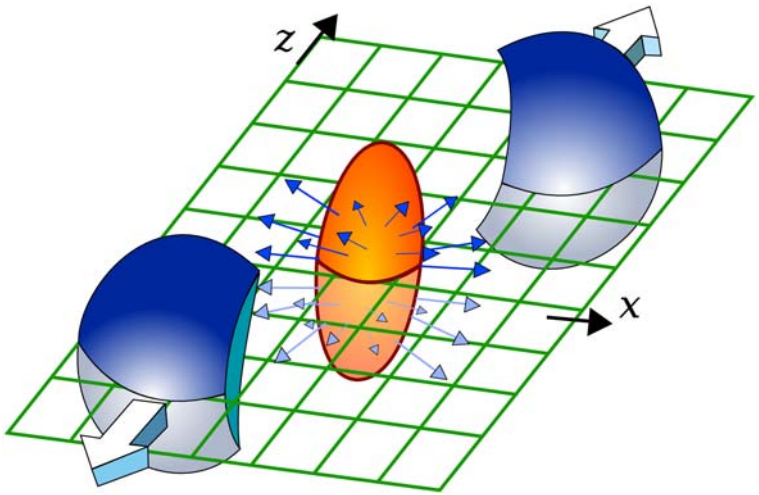


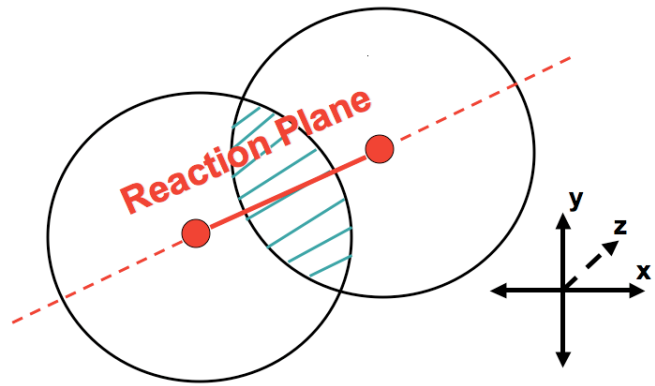


- Fast partons lose energy due to gluon density, path length
- Where does the energy go?
- How do different E-loss mechanisms contribute?
- How does the medium respond to the deposited energy?

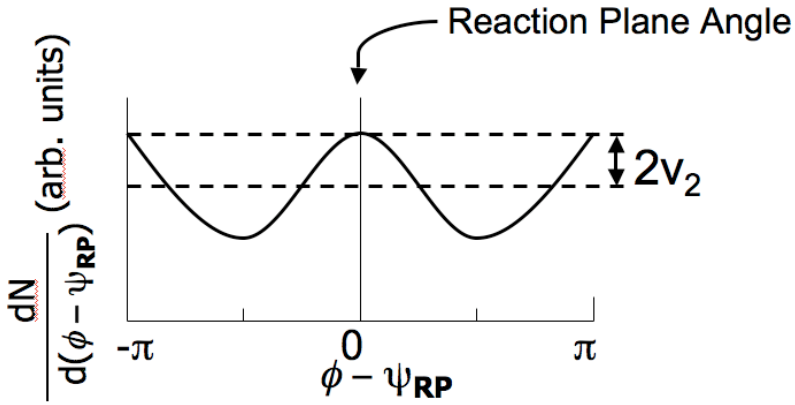
- Jet reconstruction in HI collisions is *hard*
- Extract jet physics from azimuthal correlations

The Reaction Plane (and Flow)





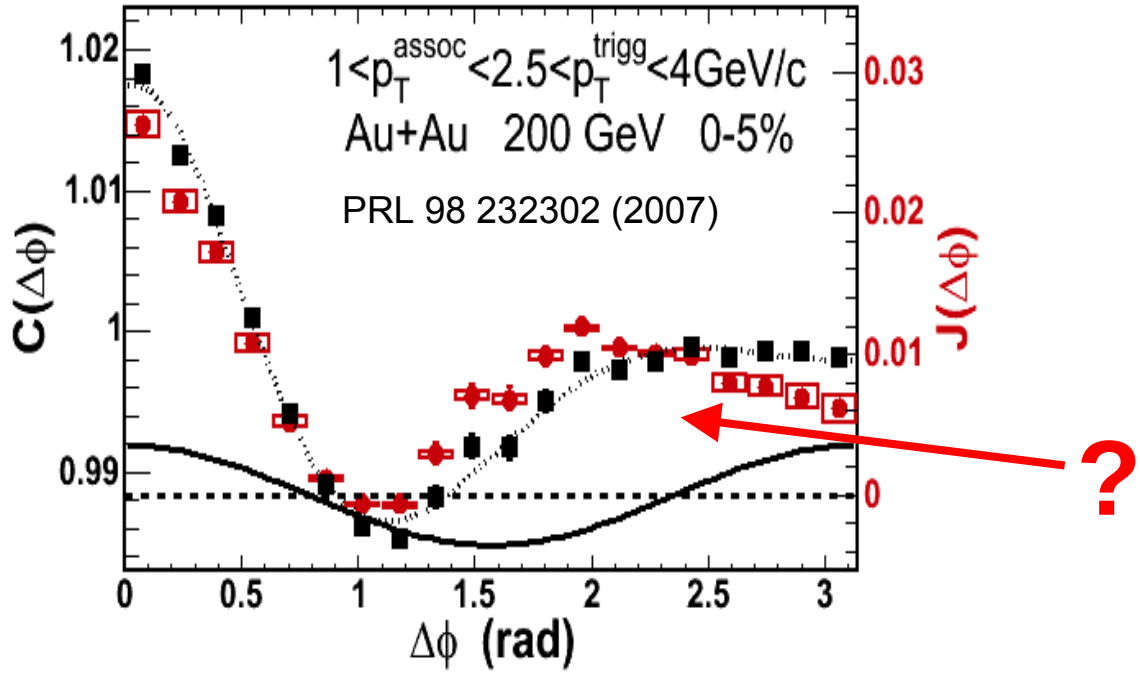
$$\frac{dN}{d\Delta\varphi} = \frac{1}{2\pi}\sum_n (1 + 2v_n \cos n\Delta\varphi)$$



- Spatial anisotropy in colliding zone leads to pressure gradients and anisotropy in momentum space
- Additional source of two-particle correlations ⇒ one physicist's signal is another physicist's background

Correlations and Multiple Sources

$$C(\Delta\phi) = \frac{N_{same}}{N_{mixed}}$$

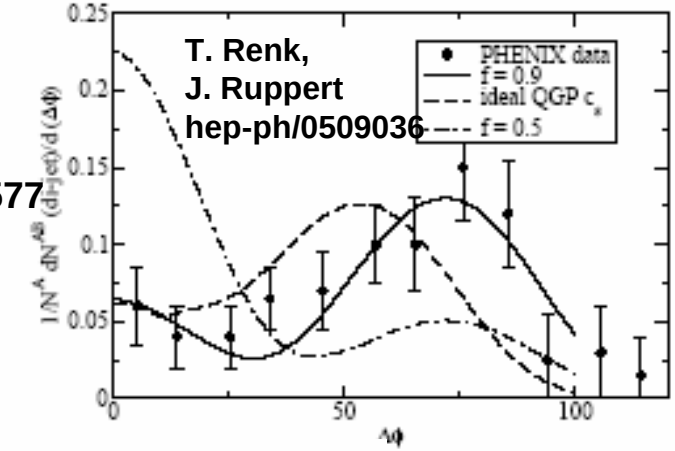


- Two sources of correlation:
  - $C(\Delta\phi) = J(\Delta\phi) + Flow(\Delta\phi)$
- Extraction of $J(\Delta\phi)$ requires careful subtraction of flow contribution (eg. ZYAM method)
- Pair yield near $\Delta\phi = 0$ and $\Delta\phi \approx 2$ (away-side modification)

Sources of Away-side modifications

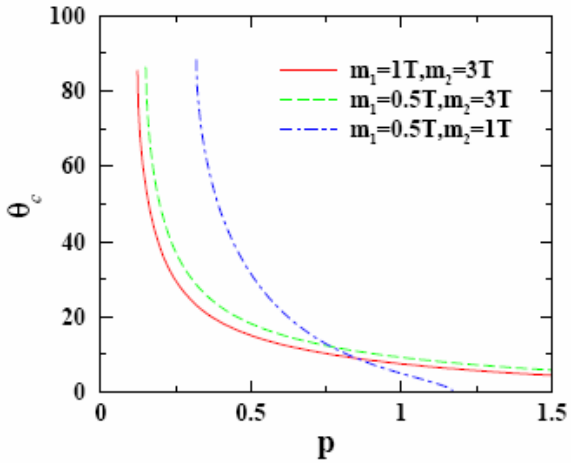
- Mach cone / sonic boom

Casalderrey-Solana, Shuryak, Teaney, Nucl. Phys. A774 (2006) 577
H. Stoecker, Nucl. Phys. A750 (2005) 121
J. Ruppert & B. Mueller, Phys. Lett. B618 (2005) 123



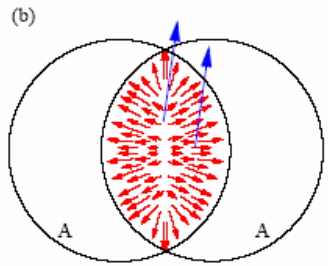
- Cherenkov gluon radiation

Koch, Majumder, Wang, PRL 96 (2006) 172302



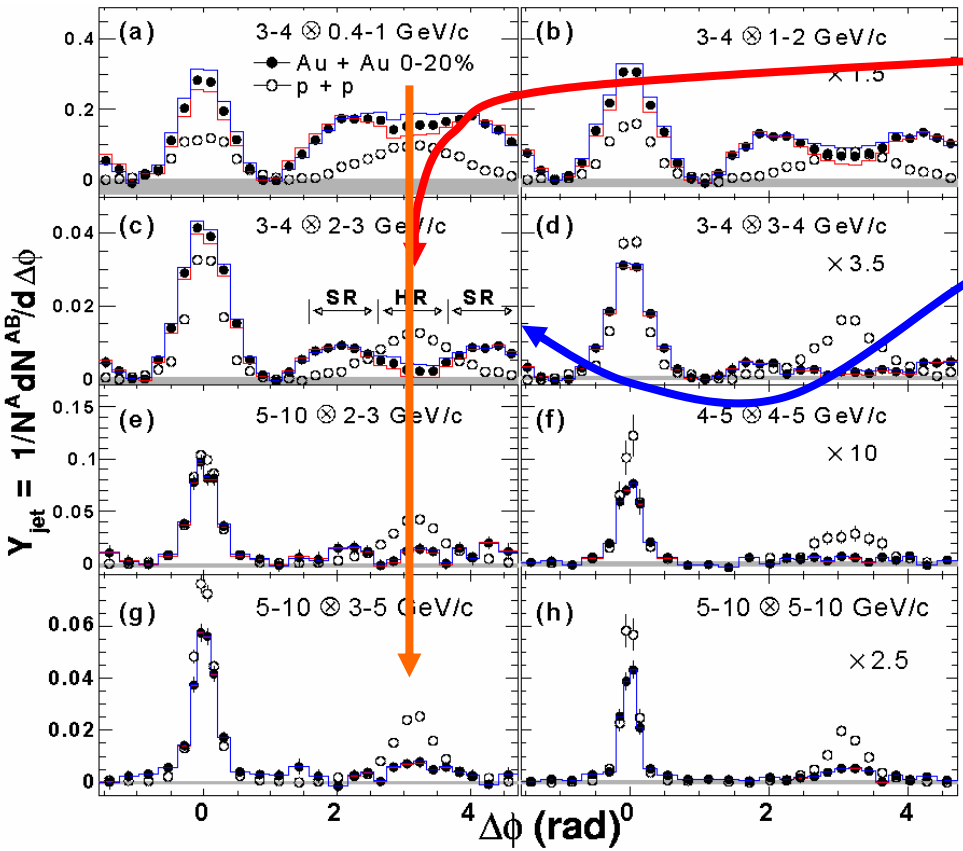
- Coupling of jets and flow

Armesto,Salgado,Wiedemann, PRC 72 (2005) 064910



Evolution of the (inclusive) Jet Shape

Au+Au & p+p √s = 200 GeV



Per-trigger yield vs. $\Delta\phi$ for various trigger and partner p_T ($p^A_T \otimes p^B_T$), arranged by increasing pair momentum ($p^A_T + p^B_T$)

PRC 77 011901 (2008)
arXiv:0801.4545v1 [nucl-ex]

- Establish the punch-through jet component ("Head Region")
- and the medium-induced component ("Shoulder Region")

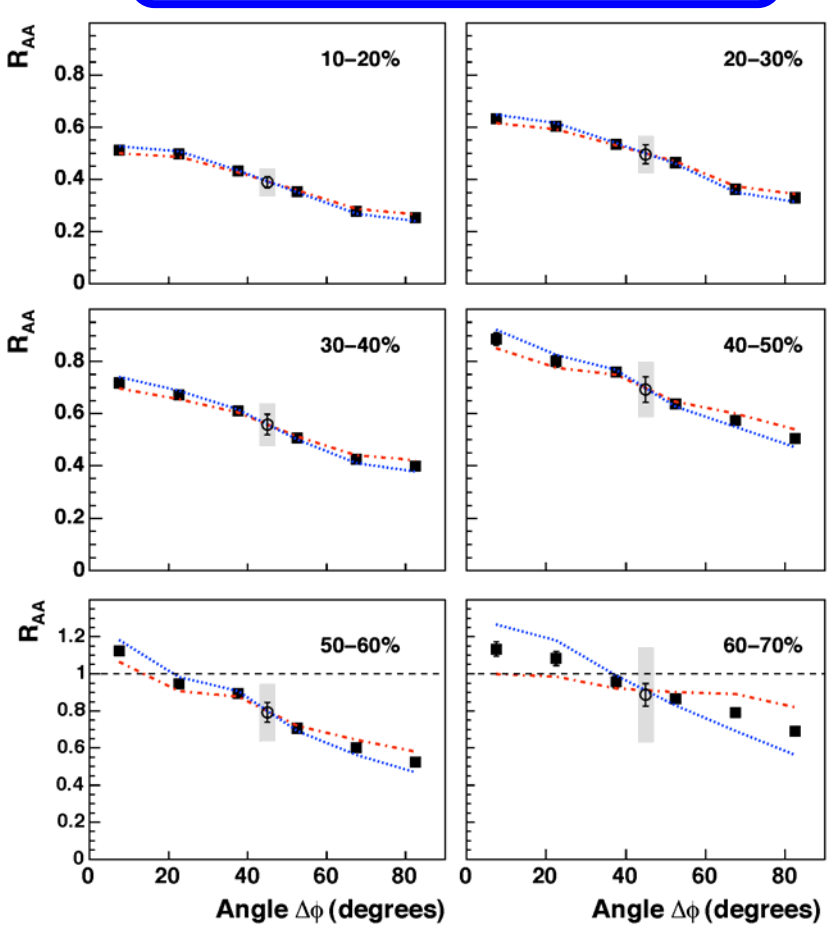
- Evolves from flat → concave → convex
- Suppression in HR, Enhancement in SR
- Reappearance of peak is not due to merging of side peaks. High p_T is consistent with jet fragmentation.
- Current conjecture:
  - Head region ⇒ jet modification (dominant at high p_T)
  - Shoulder region ⇒ medium response (dominant at intermediate p_T)

Going Beyond Inclusive Measurements

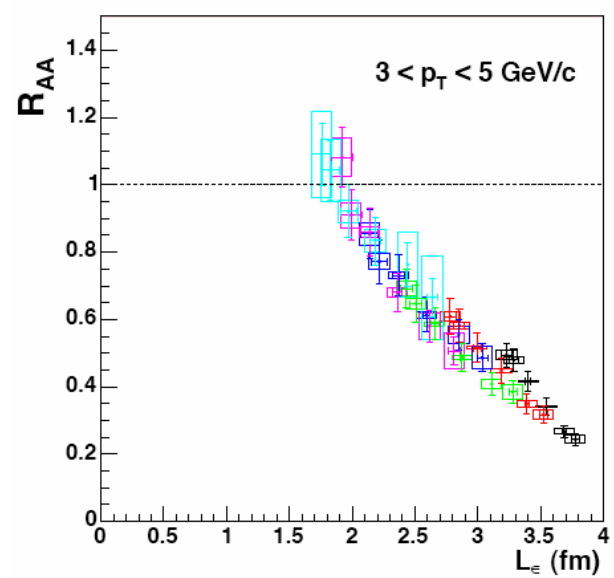
R_{AA} π^0 in AuAu $\sqrt{s}$=200 GeV vs. Reaction Plane

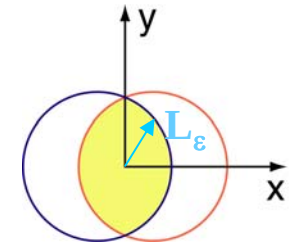
PRC76, 034904 (2007)

$R_{AA}(\Delta\phi)$ vs. centrality varies density of and distance through medium



$3 < p_T < 5$ GeV/c



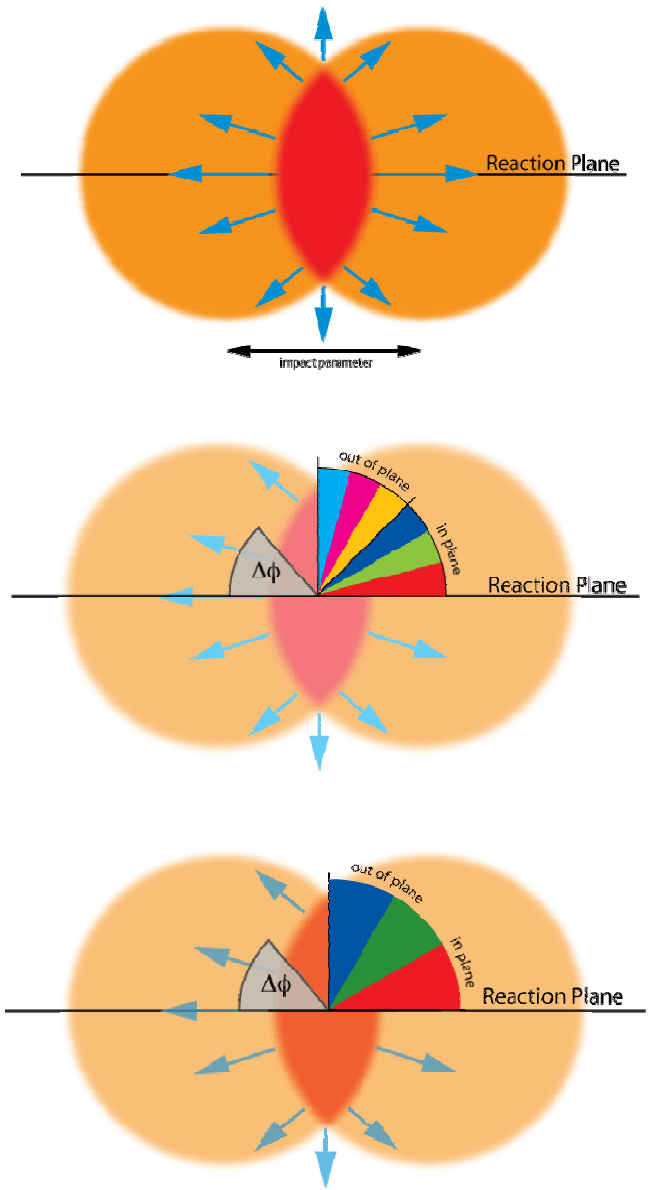


L_ε = distance from edge to center of participants calculated in Glauber model

Little/no energy loss for $L_\varepsilon < 2$ fm

- Advantage of R_{AA} over v_2: relative nature of v_2 hides the geometric dependence of energy loss.
- L_ε Caveats – the result is tantalizing, but:
  - Too simple a picture (!)
  - Implies something other than radiative E-loss
  - Blind luck, or some mechanism we don't understand?
- Will apply analysis to higher p_T data

Jets: Controlling path length effects



- Fix the centrality
  - Constrains energy density
- Orient trigger particle *wrt* reaction plane
  - Varies effective path length of jet
- Constrain path length dependence of energy loss to untangle jet and medium response

High-p_T measurement with PHENIX

EMCAL --- measure energy deposit of electrons and gammas

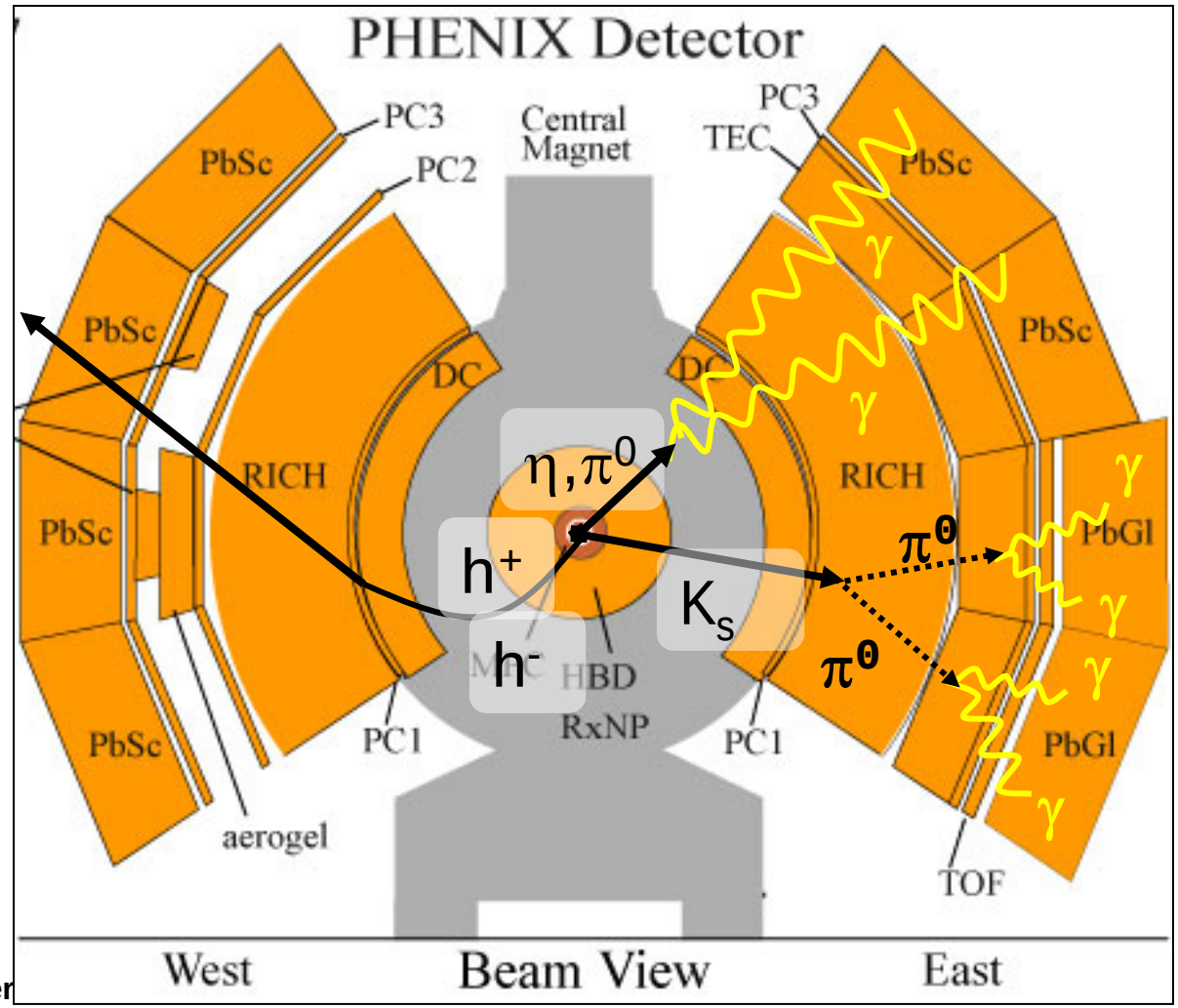
DC --- obtain momentum of charged particles

PC --- measure hit position of charged particles

Tracking and Matching (DC, PC)
→charged hadrons

EMCAL (PbSc + PbGl)

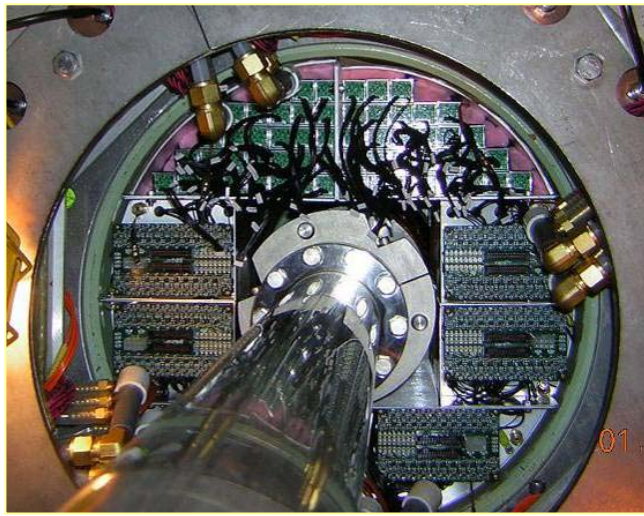
→η,π^0,Ks

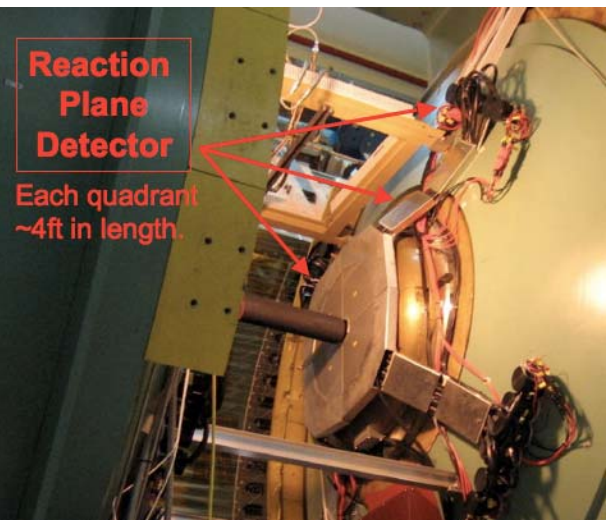


Reaction Plane Measurement with PHENIX

Beam-Beam Counters

- Quartz Cherenkov radiators
- 64 elements in 3 rings
- $3.0 < |\eta| < 4.0$
- All Runs





Reaction Plane Detector

- plastic scintillators @ $38<|z|<40$cm
- 12 segments in ϕ
- 2 segments in η
  - $1.0 < |\eta| < 1.5$
  - $1.5 < |\eta| < 2.8$
- Pb converter
- Run 7+

Muon Piston Calorimeter

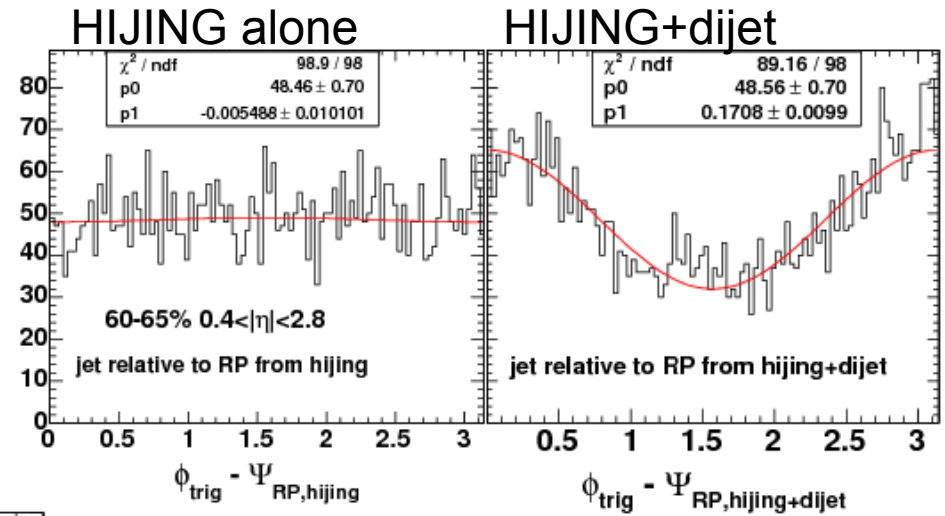
- $PbWO_4$ PHOS crystals
- 192 towers
- $3.1 < |\eta| < 3.7$
- Run 6+

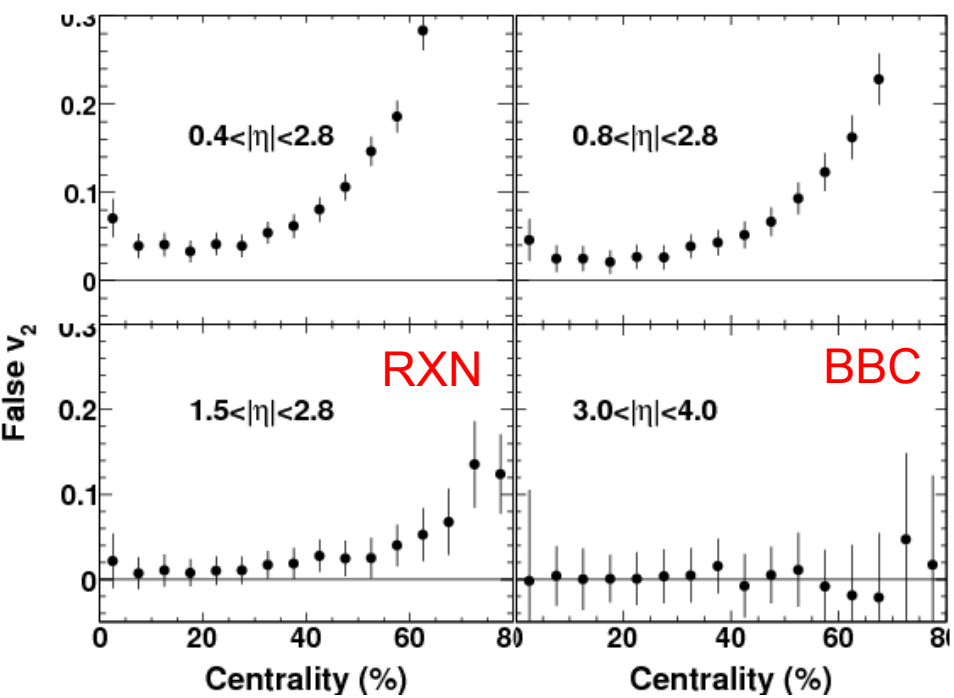
Multiple overlapping and complementary measurements

Non-flow effects?

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

Trigger relative to RP

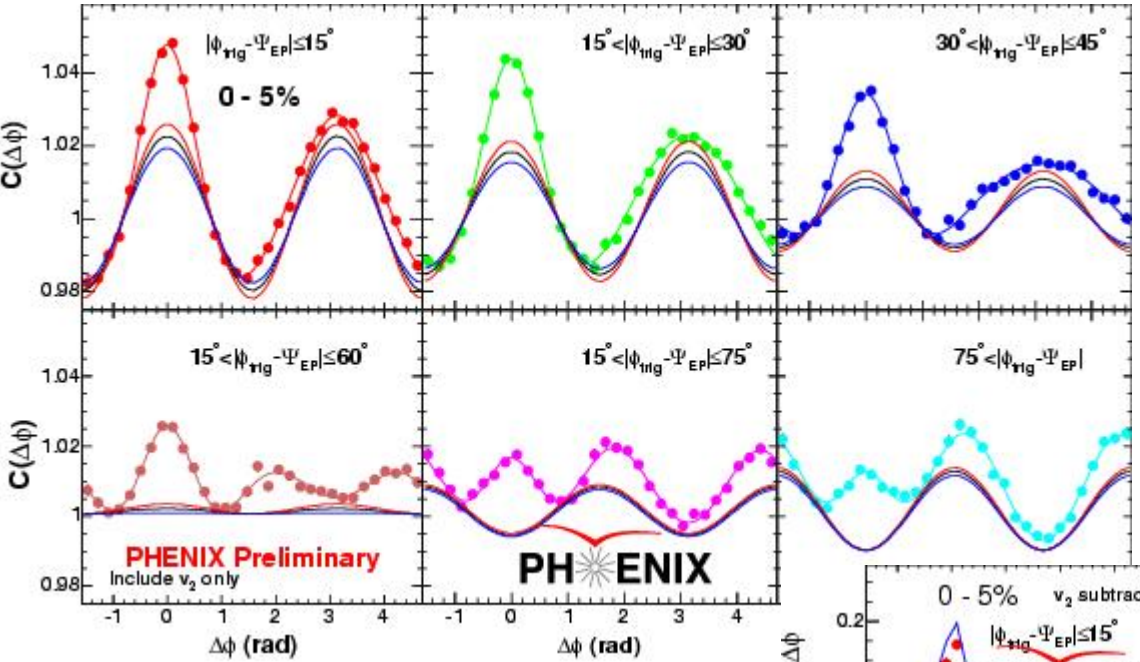




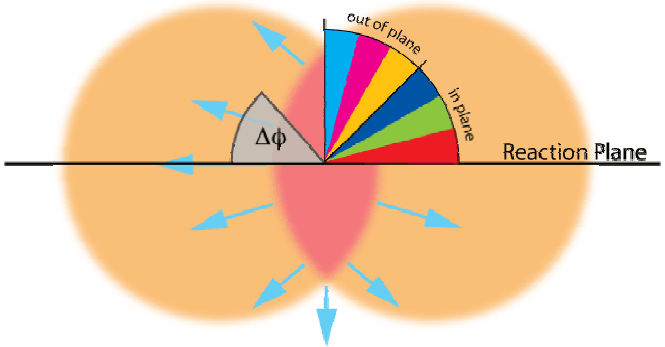
- Measure "fake" v_2 of jets
- Effect varies as function of η where v_2 is measured

arXiv:0801.4545v1 [nucl-ex]

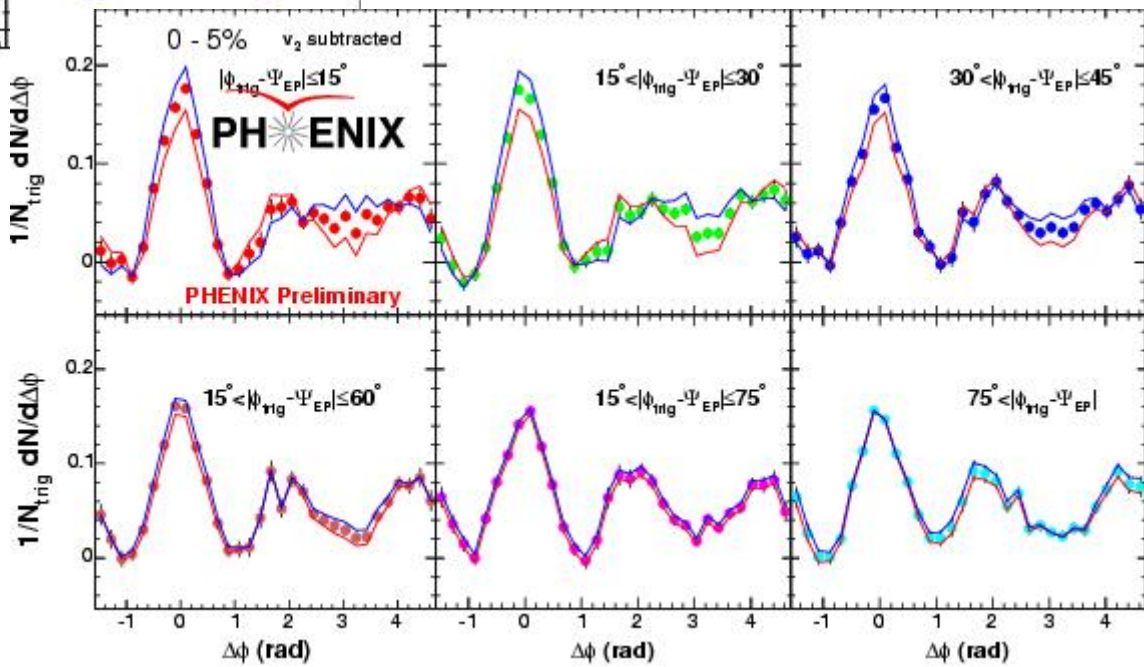
Au+Au Correlation and Jet Functions



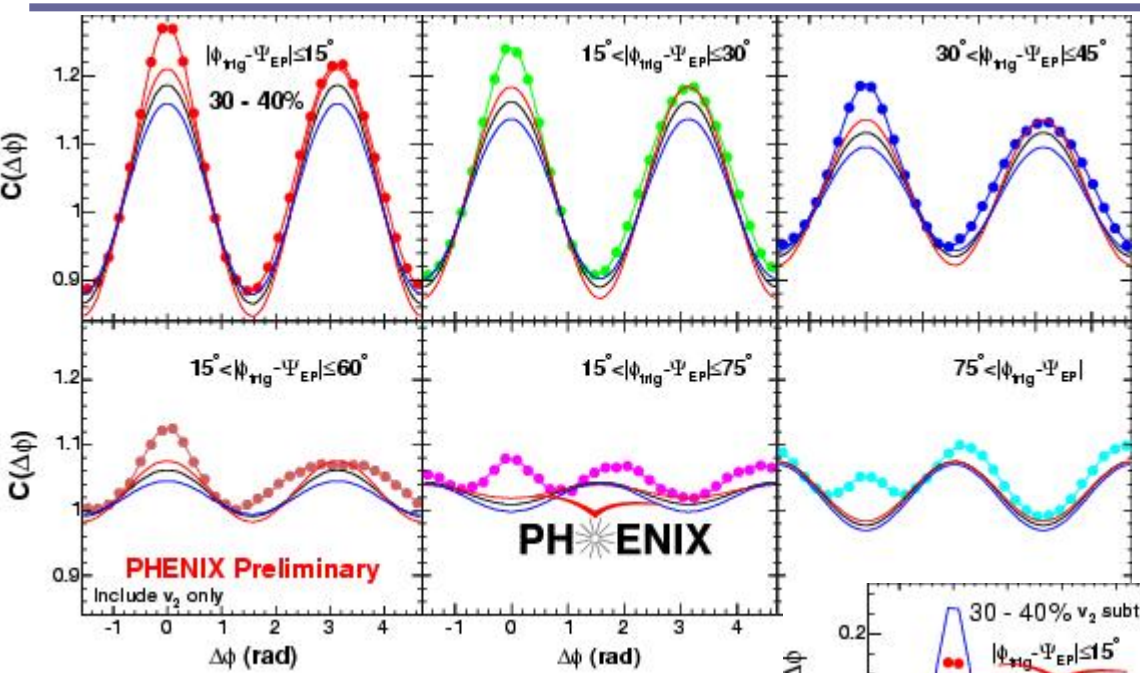
Run 4 Au+Au 200 GeV
0-5 % Centrality



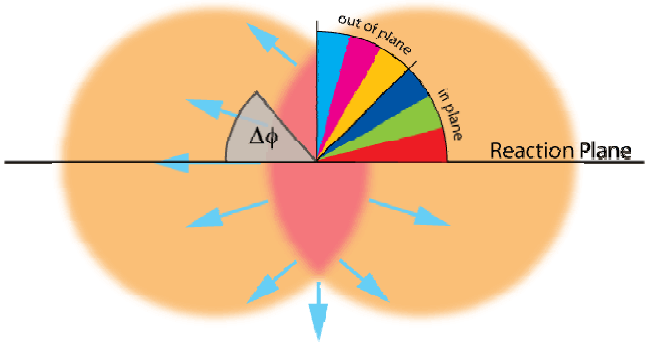
- Correlation functions: Significant RP-dependence (even in 0-5!)
- No RP-dependence in Jet functions



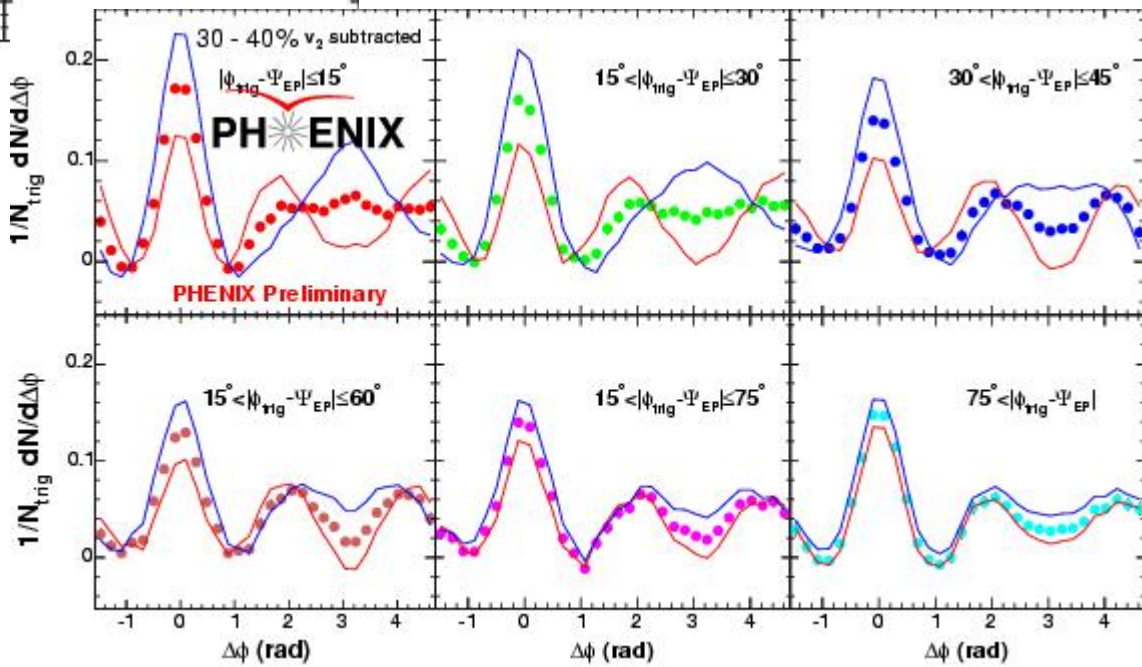
Au+Au Correlation and Jet Functions



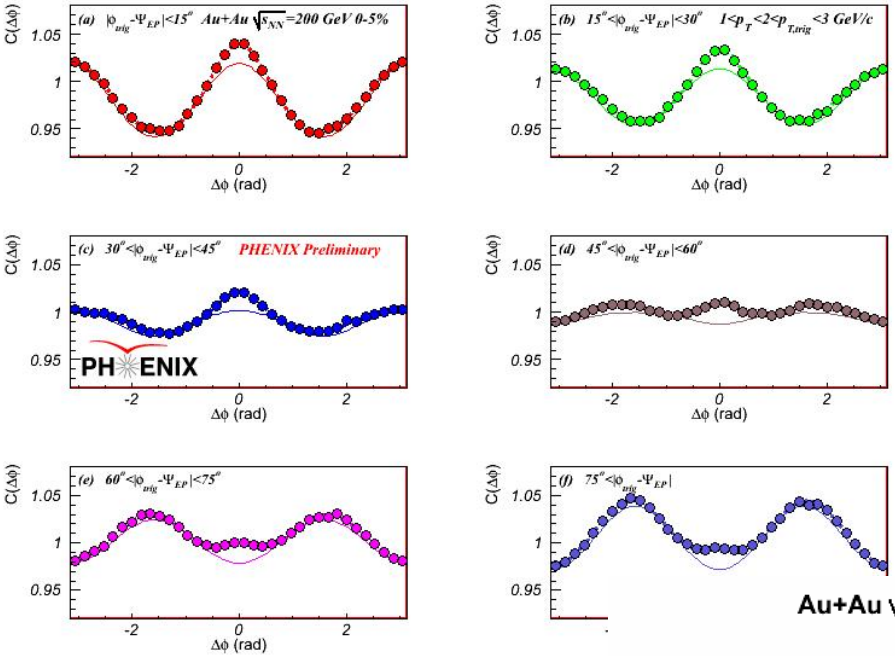
Run 4 Au+Au 200 GeV
30-40 % Centrality



- Central and semicentral exhibit same trends



Run7 Au+Au with Reaction Plane Detector

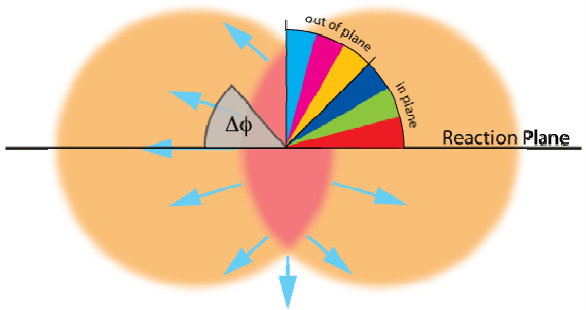


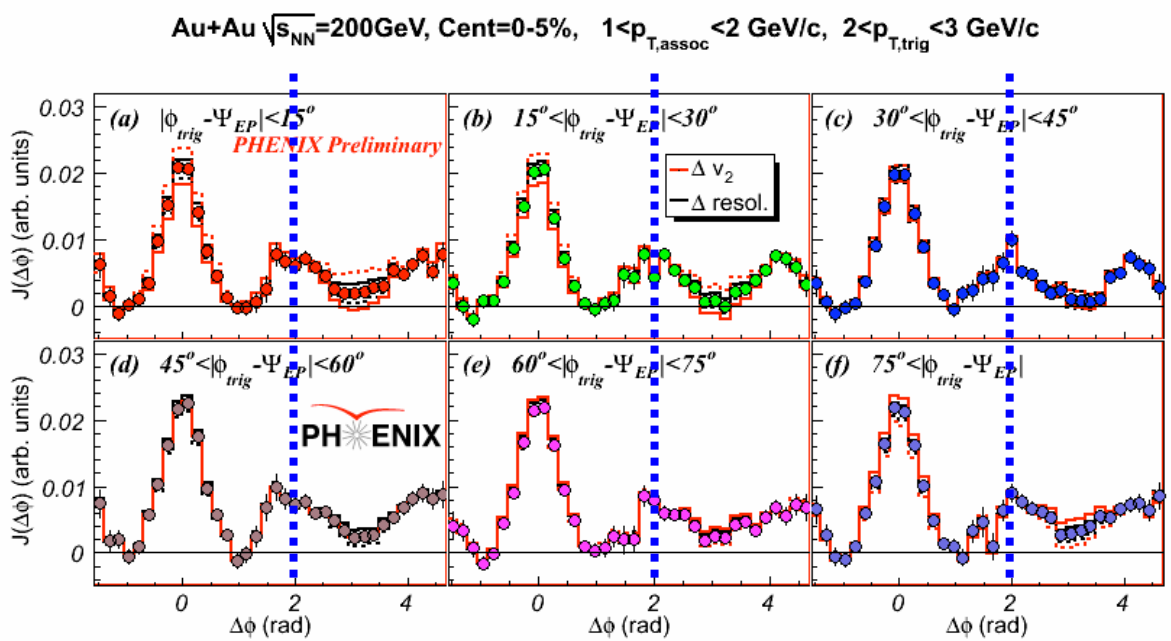
Au+Au √s=200 GeV 0-5% Centrality

Left: Correlation functions

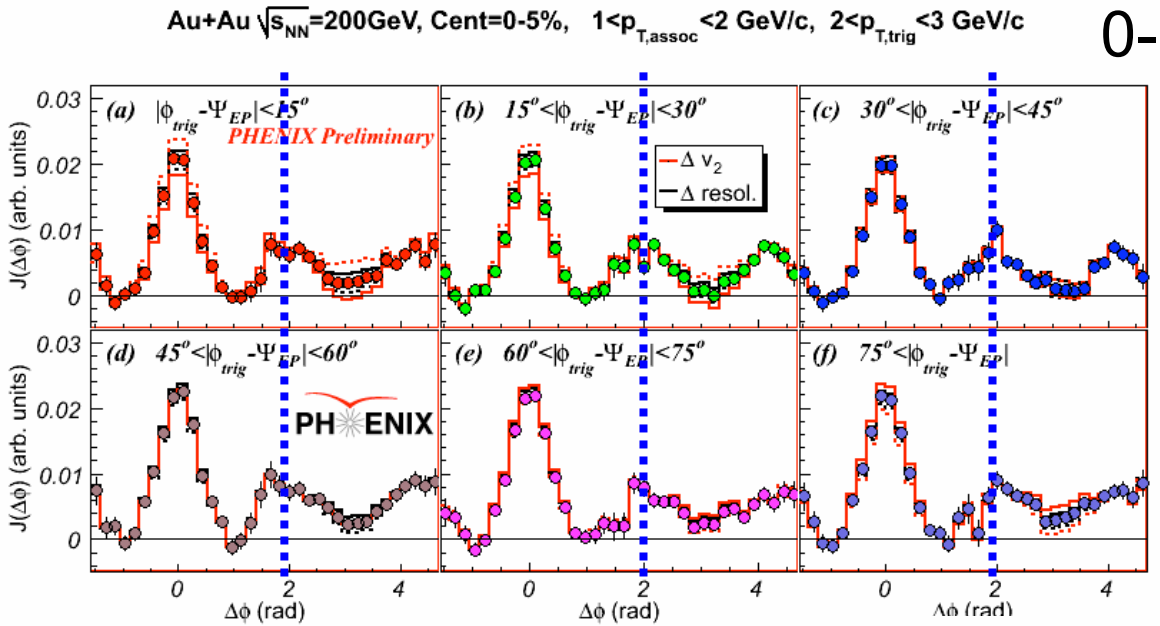
Below: Jet Functions

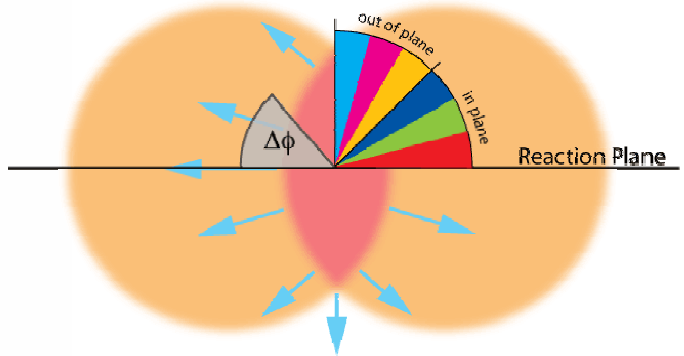
RP from Reaction Plane detector



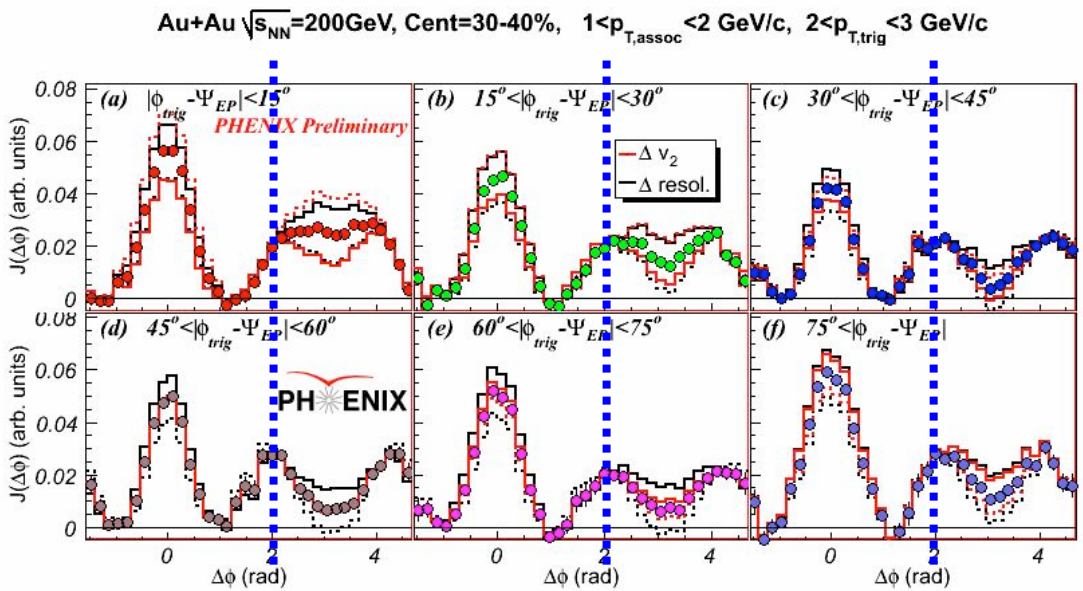


Run7 Au+Au Jet functions



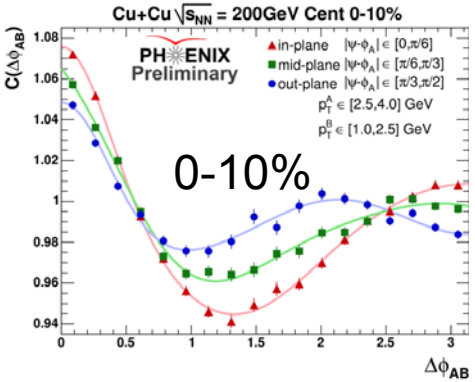


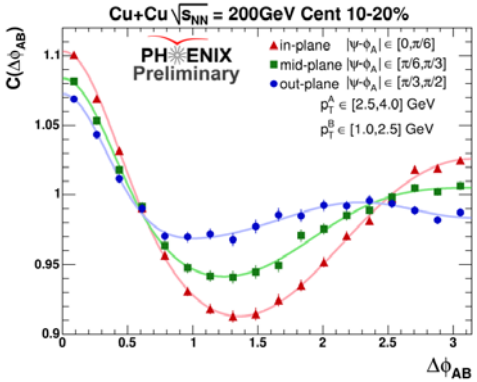
30-40 %

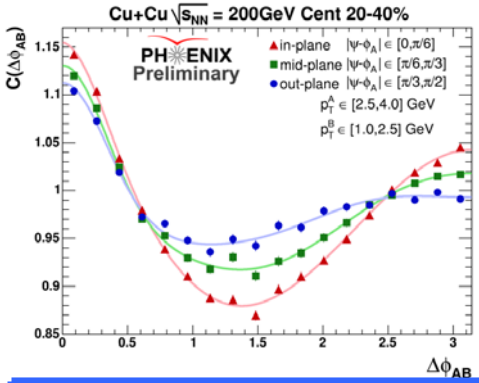


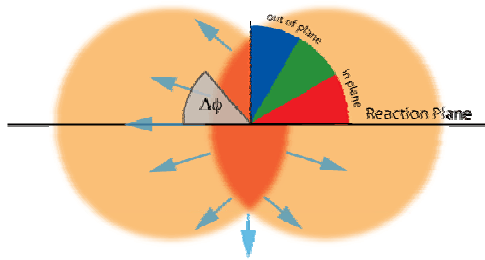
- Head region sensitive to path length variation
  - Consistent with energy-loss expectation
- Shoulder region insensitive to path length
  - Inconsistent with jet-flow coupling
  - NOT inconsistent with mach cone scenarios

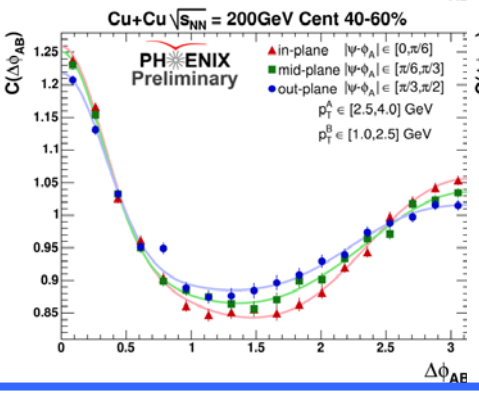
Cu+Cu Correlation and Jet Functions

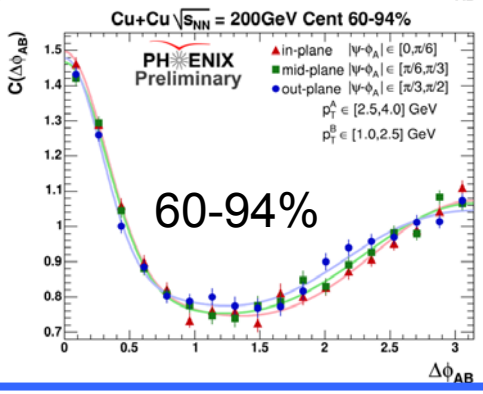


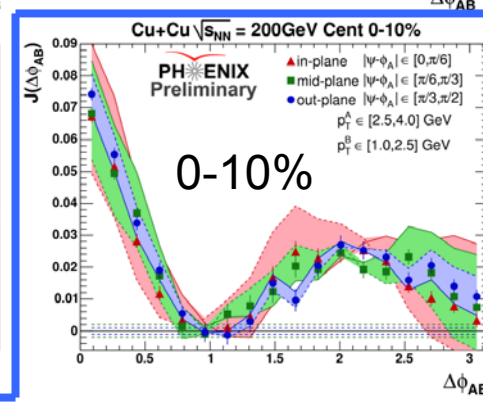


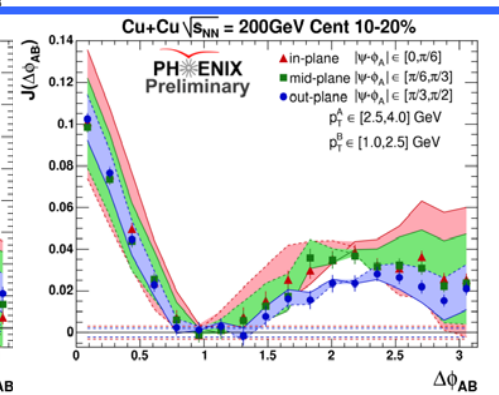






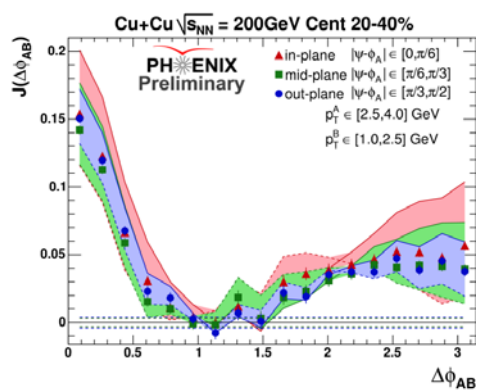


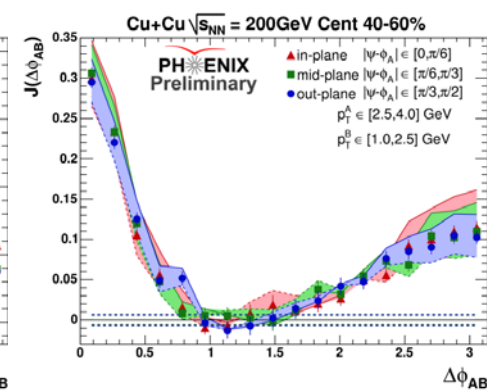


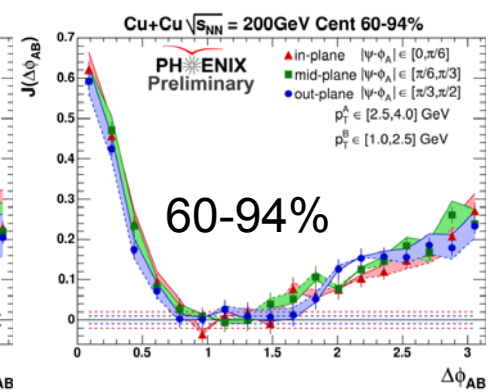


<u>Within a centrality</u>:

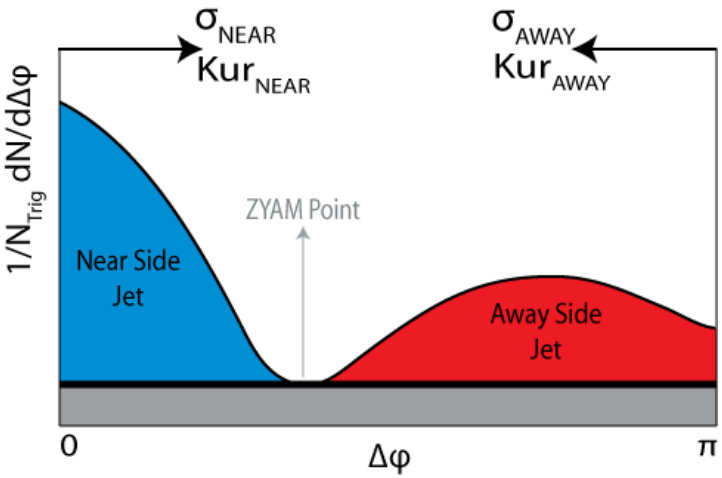
- Correlation functions: clear angular dependence
- Jet functions: no RP dependence within errors

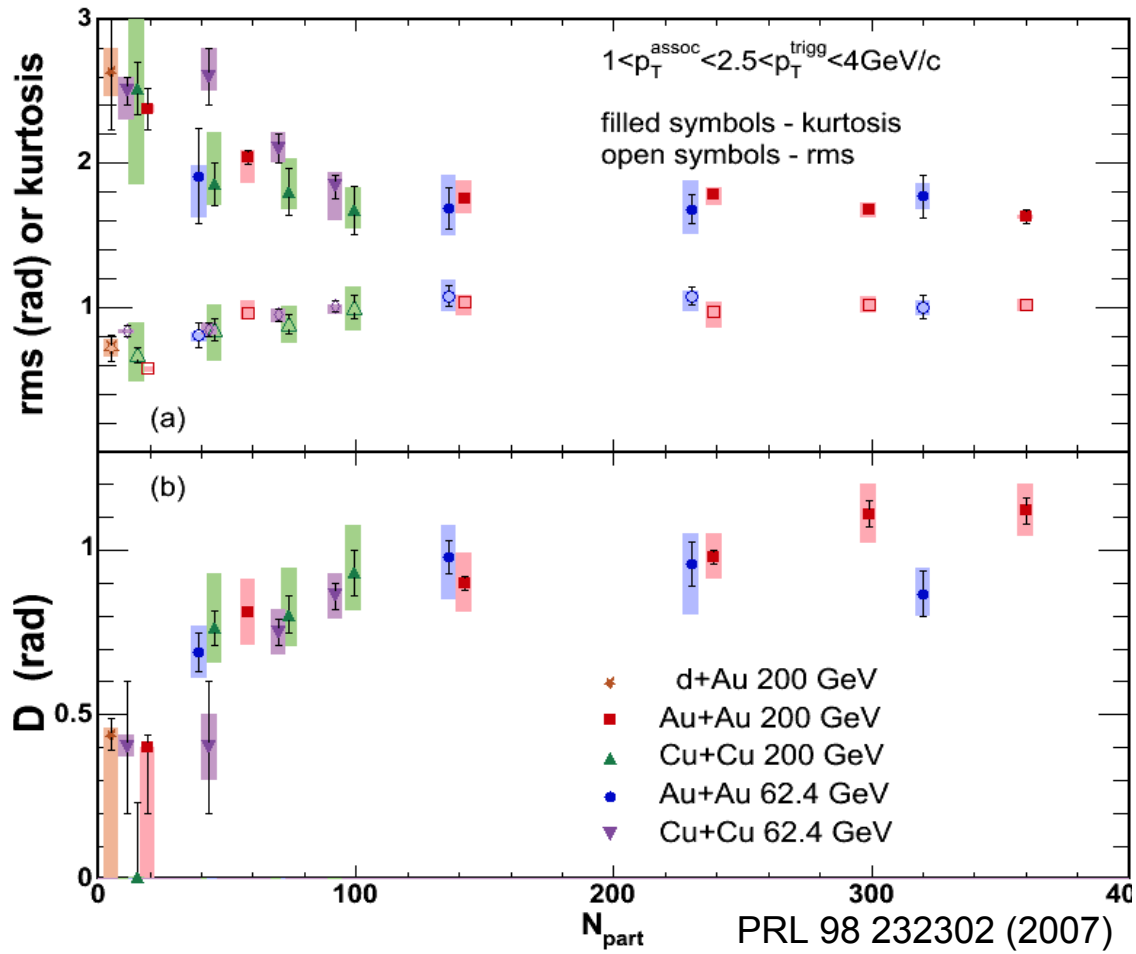






Shape Parameters Review

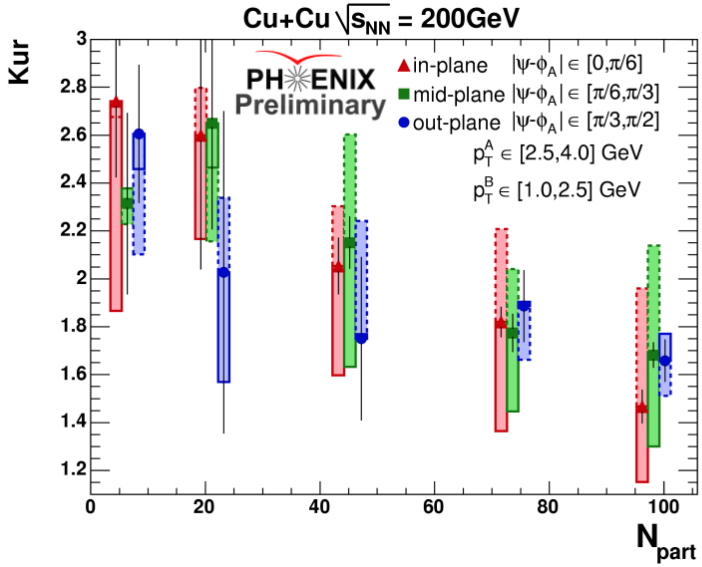


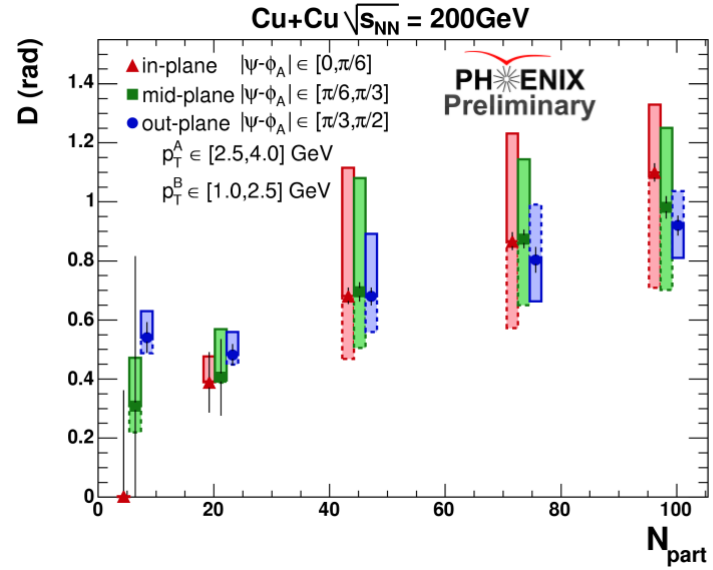


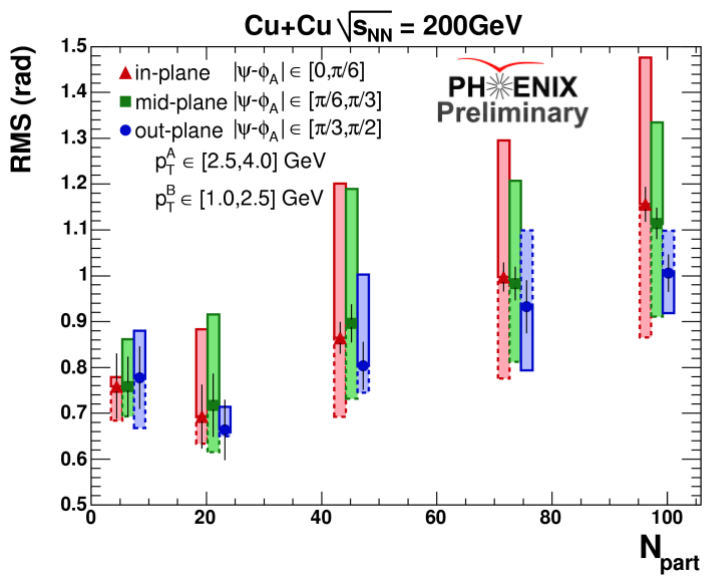
PRL 98 232302 (2007)

- Characterize peak shape:
  - RMS
  - Kurtosis
  - Away-side double Gaussian fit: Offset ±*D*
- Saturates for N_{part}>100
- Disfavors certain models
  - Eg. Cherenkov gluon radiation
- Constrains others
  - Eg. Non-Cherenkov gluon radiation at large angles

Shape Parameters vs. RP (Cu+Cu)

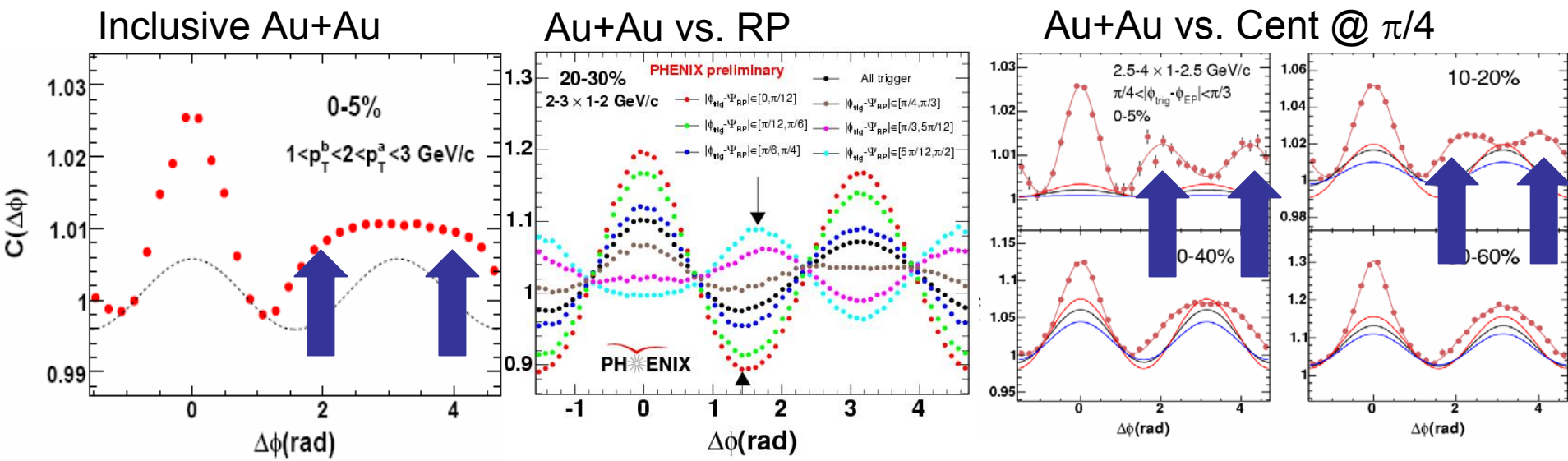






- RMS, Kurtosis, and D all exhibit same trend as inclusive data
- No discernible dependence on angle of emission wrt reaction plane

Medium effects w/o subtraction?



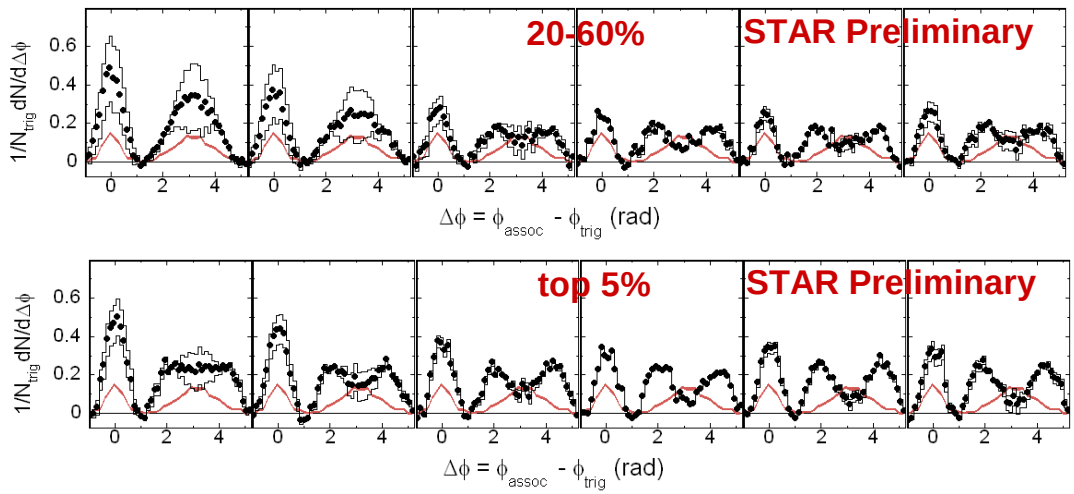
- Inclusive correlation Au+Au – Example: 0-5%
  - Modest flow in this bin
  - Background subtraction can only make effect more pronounced
- Choose a trigger orientation with minimal impact from modulated background
  - 4th bin: ~ π/4 (grey circles)
- Example: Au+Au in 4th RP bin, several centralities
  - "mach cone"(?) effect clear without any subtraction
  - Need to focus on source of shoulder!

But… what about outside PHENIX?

Mid-Central v.s. Central Collisions Comparison

$3<p_T^{trig}<4$GeV/c & $1.0<p_T^{asso}<1.5$GeV/c

in-plane $\phi_S=0$ → out-of-plane $\phi_S=90^o$



- **In 20-60%, away-side evolves from single-peak (Φ_S =0) to double-peak (Φ_S =90º).**
- **In top 5%, double peak show up at a smaller Φ_S.**
- **At large Φ_S, little difference between two centrality bins.**

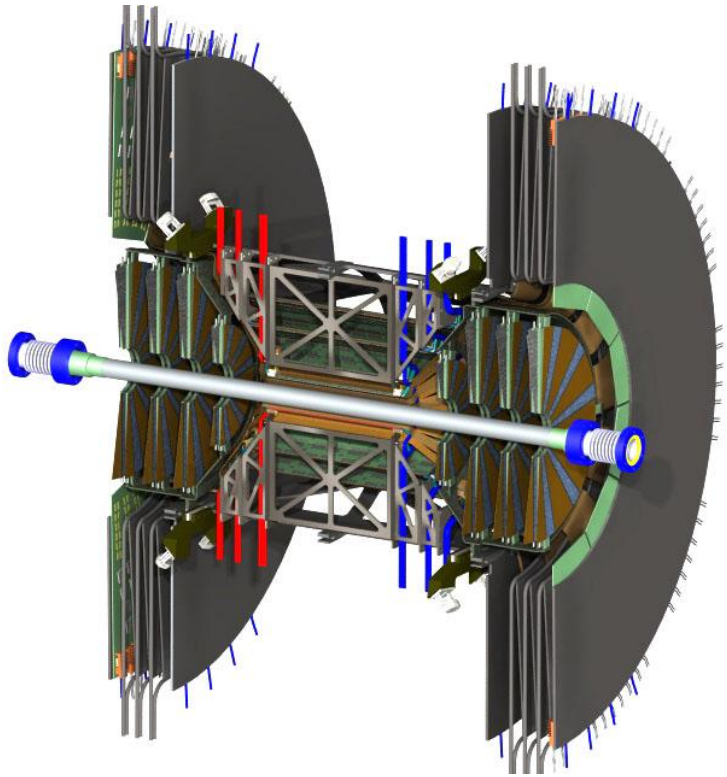
7

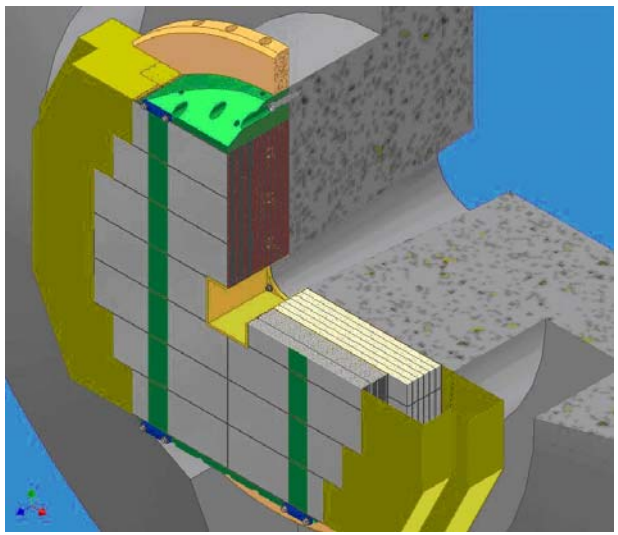
- A. Feng, QM08
  - STAR sees similar behavior

The Future

<u>Vertex and Forward Vertex Detectors</u>

- Study production and flow mechanisms of heavy quarks
- Measure reaction plane
- Improve *p* resolution
- Improve high-p_T tracking





<u>Nose Cone Calorimeter</u>

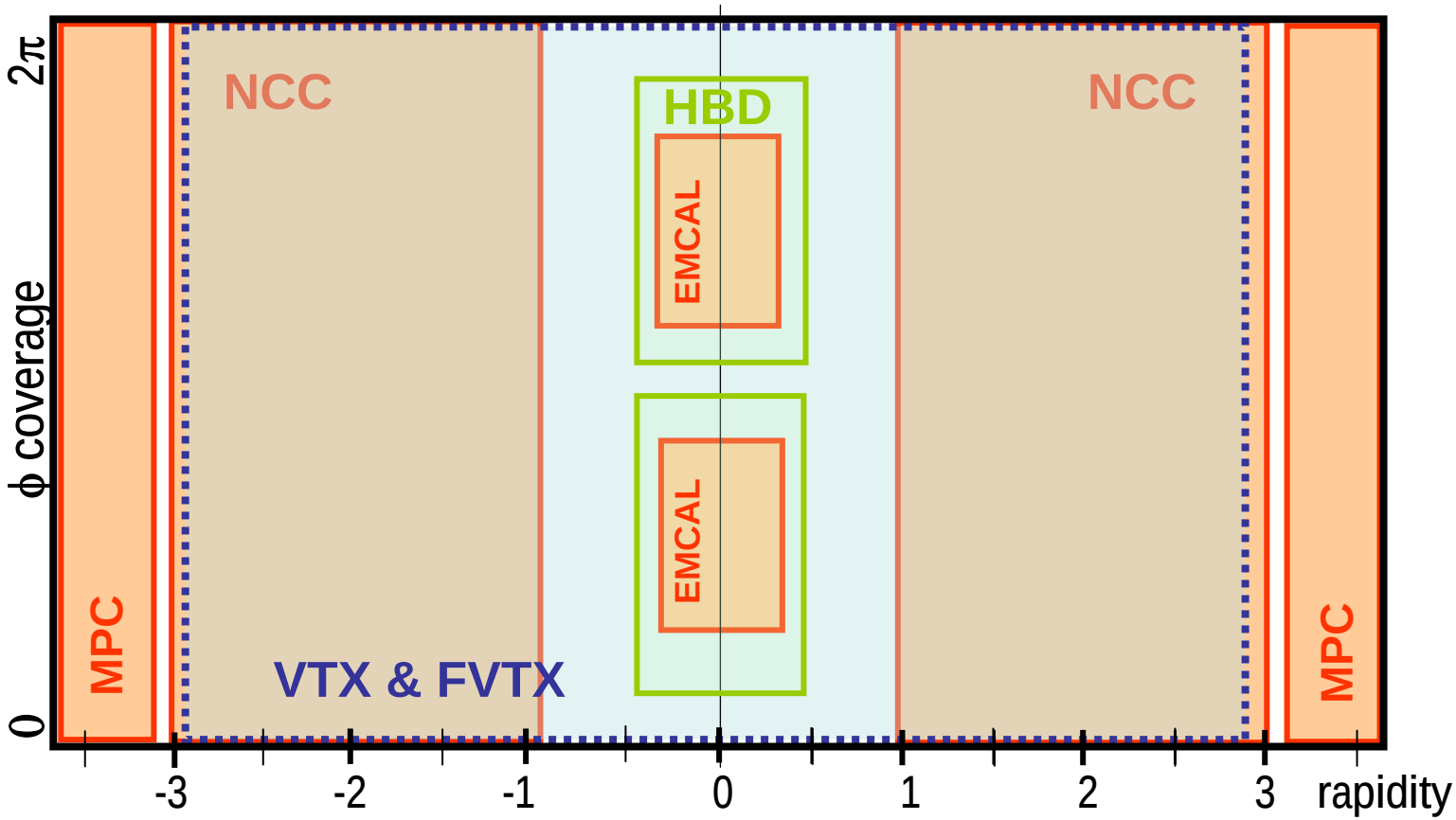
- $0.9 < |\eta| < 3.0$
- Electromagnetic and shallow hadronic compartment
- Expand kinematical coverage for jets, neutral pions, electrons, and photons to forward rapidity

Summary

- Heavy Ion data have displayed a fascinating evolution of the away side peak(s) with p_T
- Jet Observables *wrt* the reaction plane offer a further insight into energy loss of fast partons and medium response
- The shoulder region:
  - Just won't "go away", no matter what angle we look at it.
  - Appears at the about the same location, independent of:
    - Centrality
    - System size
    - *Orientation of the trigger particle*
- PHENIX jet studies vs. trigger particle's orientation tend to:
  - Disfavor Cherenkov gluon radiation and jet/flow coupling models
  - Support mach cone models
  - Provide constraints for large-angle radiation models

Backup Slides

Future PHENIX Acceptance for Upgrades



(i) π^0 and direct γ with combination of all electromagnetic calorimeters

(ii) heavy flavor with precision vertex tracking with silicon detectors

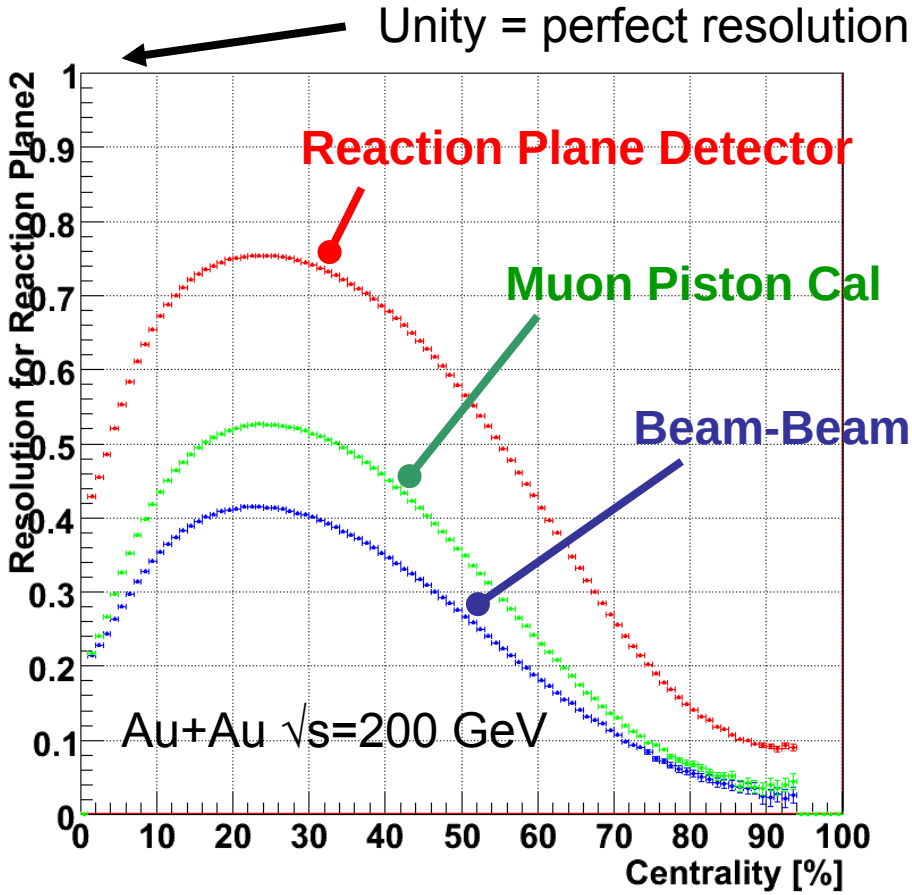
combine (i)&(ii) for jet tomography with γ-jet

(iii) low mass dilepton measurements with HBD + PHENIX central arms

Reaction Plane Resolution

- Measure reaction plane orientation using angular distribution of particles
- Finite multiplicity limits resolution of measured angle
- Correction factor extracted from comparison of independent subevents (eg. North/south detectors).

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

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

- Sub-event approach assumes:
  - Both sub-events contain the same number of particles
  - Degree of flow is the same in each sub-event
  - Any particle correlations other than flow are negligible