Azimuthal correlation and anisotropic flow measurements from the PHENIX experiment at RHIC

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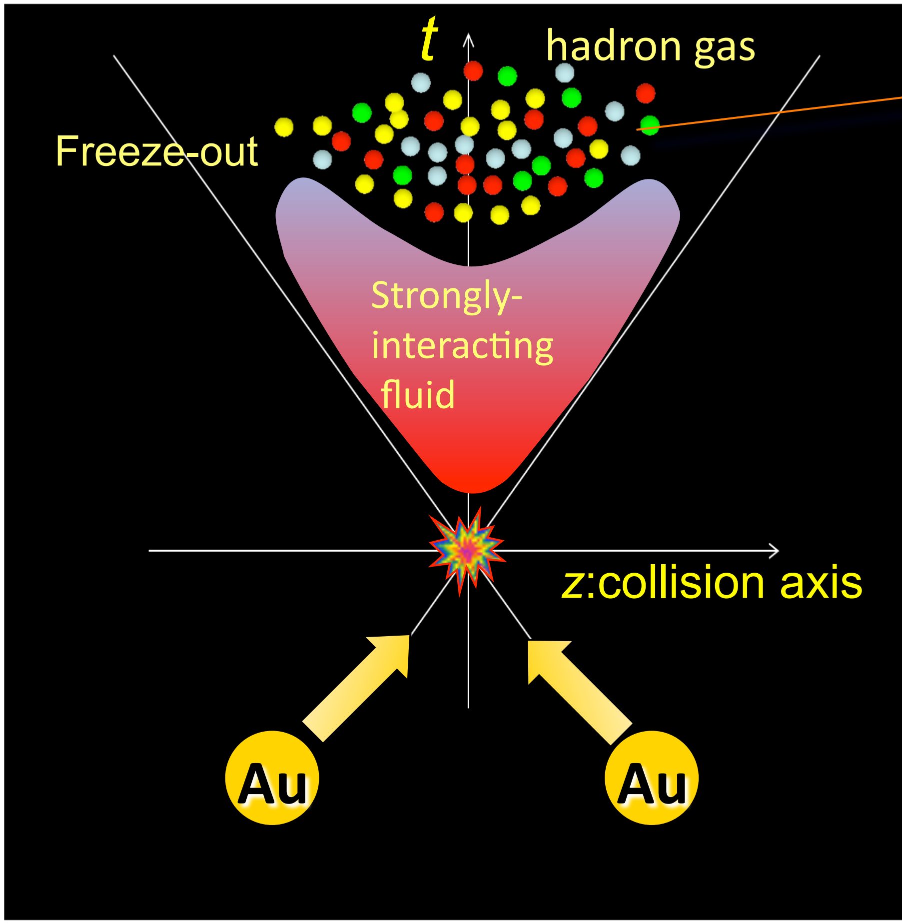
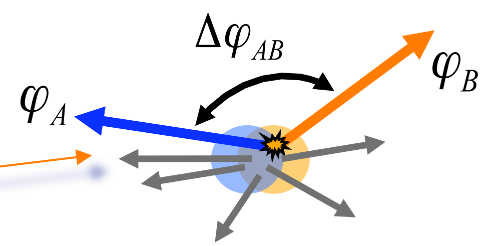
for the PHENIX Collaboration

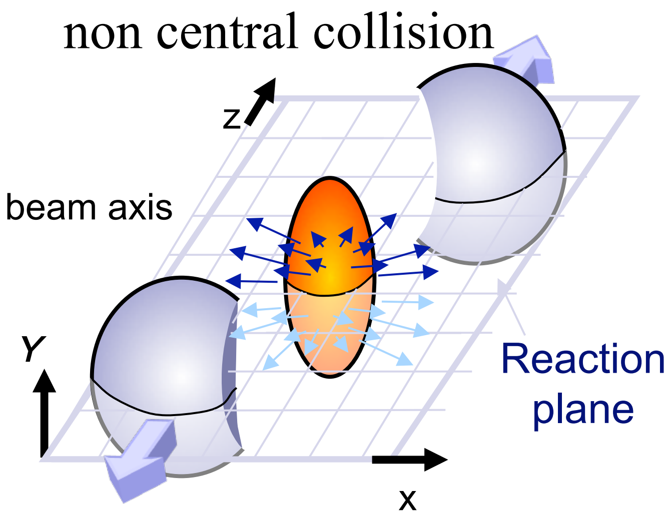
DPF 2009

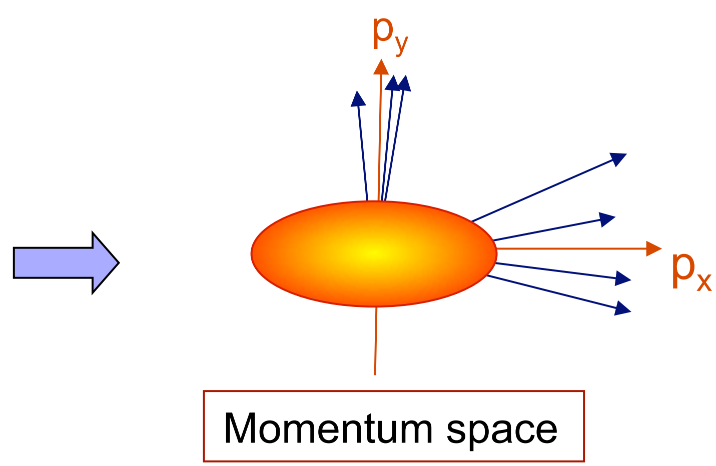
Why study correlations?





- Correlations of particles in the final state can enable us to probe early dynamics of heavy-ion collisions
- They arise due to collective flow, jets, quantum correlations, resonance decays, etc…
- Two of the most important signals are anisotropic flow and jet correlations
- In this talk, I will focus on selected results of anisotropic flow and azimuthal correlations at low and intermediate p_T





➢ Anisotropic flow is the correlation between the azimuth $\varphi = \tan^{-1}(p_y/p_x)$ of the produced particles and the reaction plane

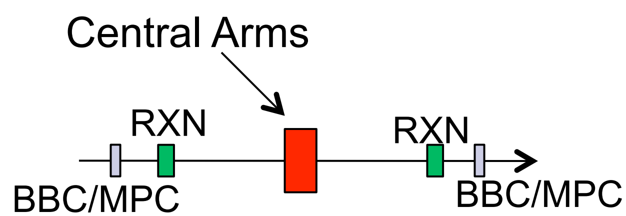
Fourier expansion of the distribution of φ with respect to the RP

$$\frac{dN}{d\phi} = n[1 + 2v_2 \cos 2(\phi - \Phi_{RP}) + 2v_4 \cos 4(\phi - \Phi_{RP})]$$

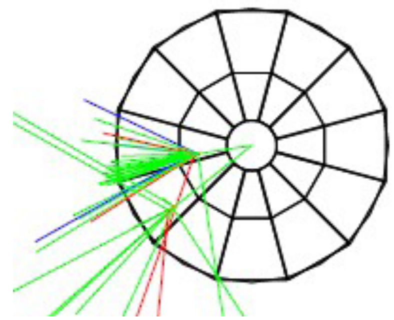
Elliptic flow (v_2)

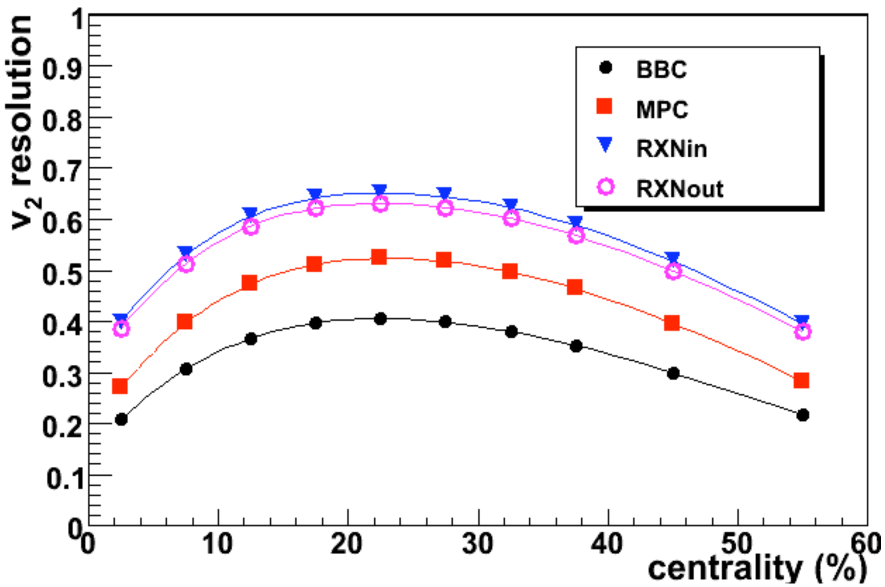
Hexadecapole flow (v_4)

Several detectors used for reaction plane determination



New RXN detector





Event planes rapidity range

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

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

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

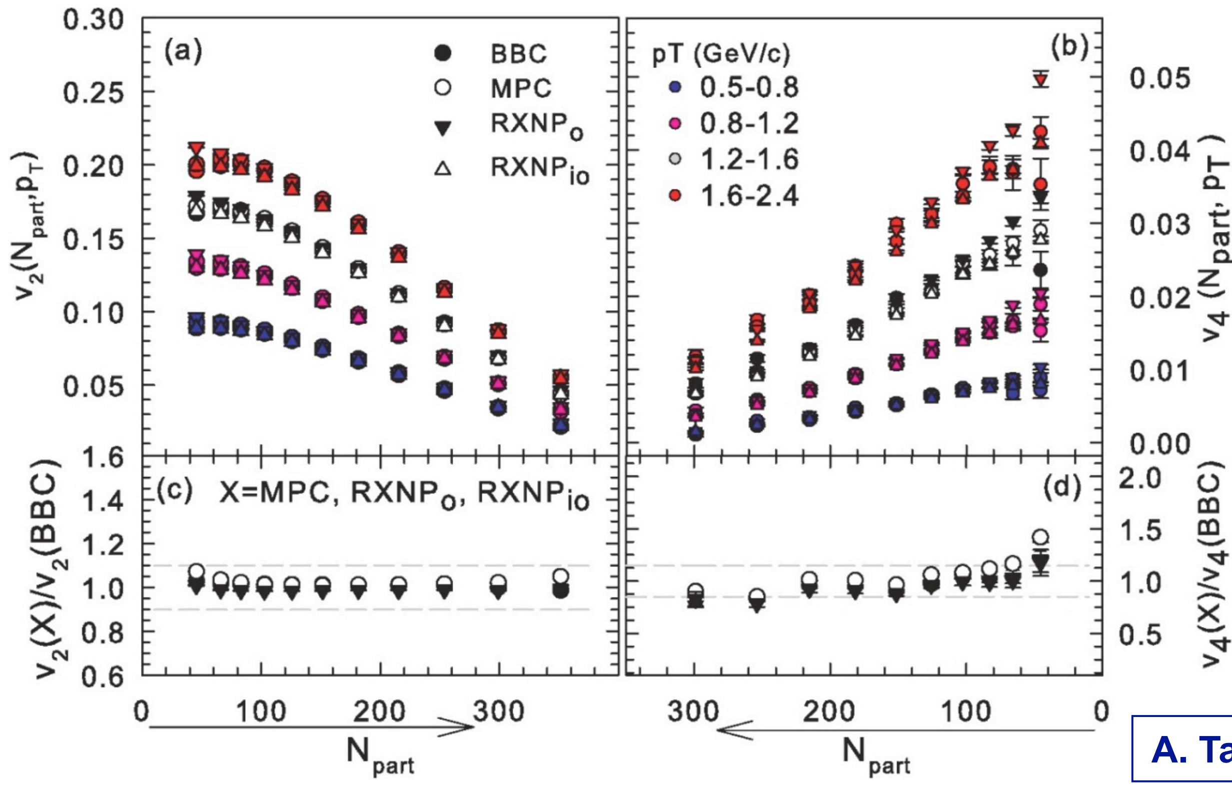
$$1.0 < |\eta_{RXNo}| < 1.5$$

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

Differential measurements of v_2 and v_4 using different detectors

Au+Au at $\sqrt{s_{NN}}$ = 200 GeV

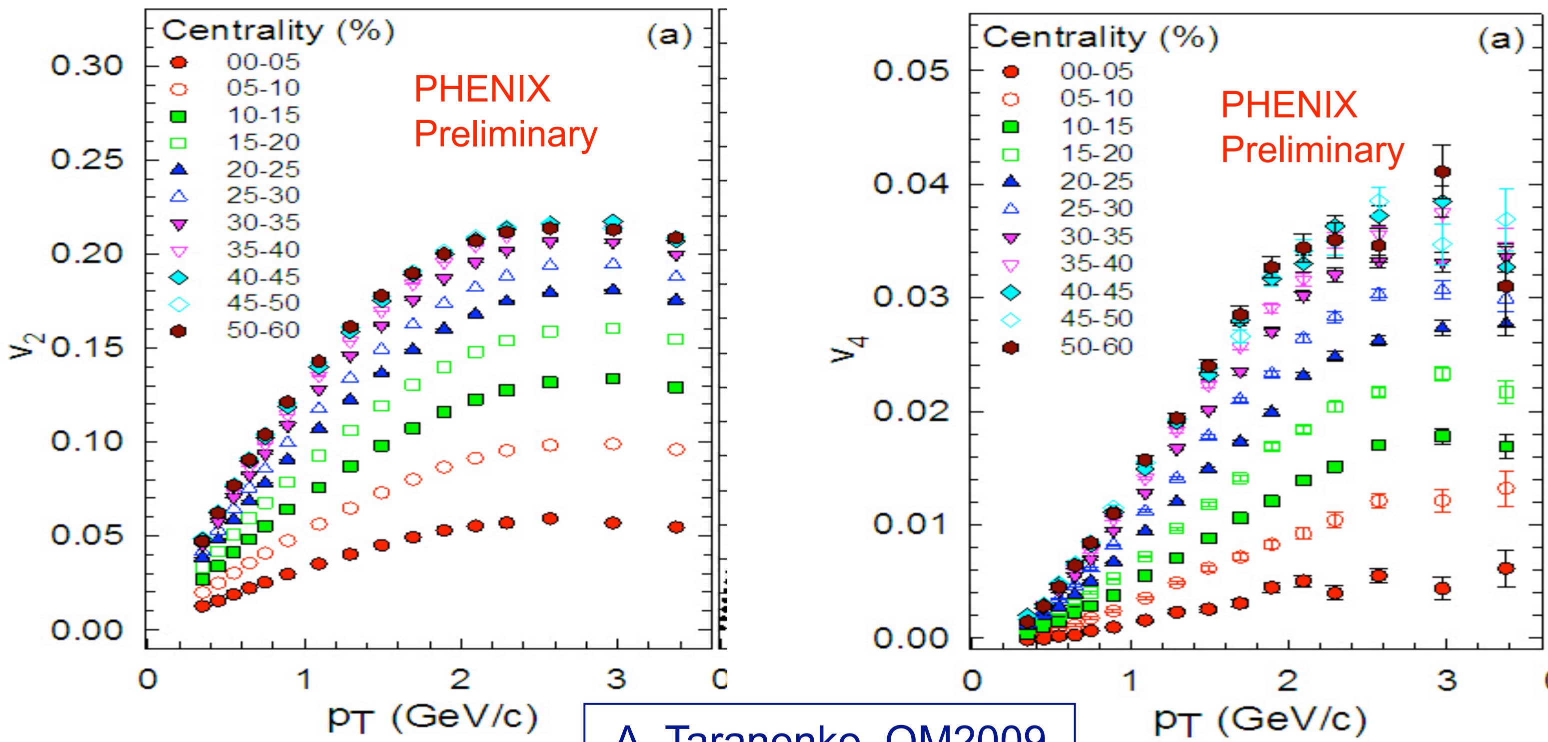
PHENIX Preliminary



A. Taranenko, QM2009

- v_4 : small but sensitive observable (P. Kolb, PRC 68, 031902(R) (2003))
- Same results of v_2 and v_4 obtained using several detectors for event-plane determination

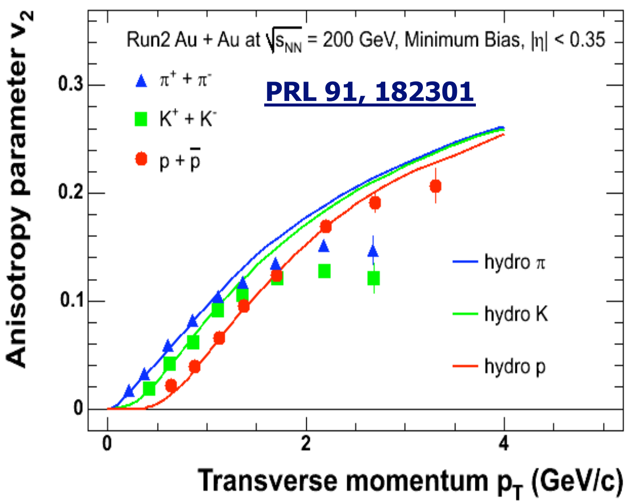
v_2 and v_4 of charged hadrons in Au+Au collisions at 200 GeV



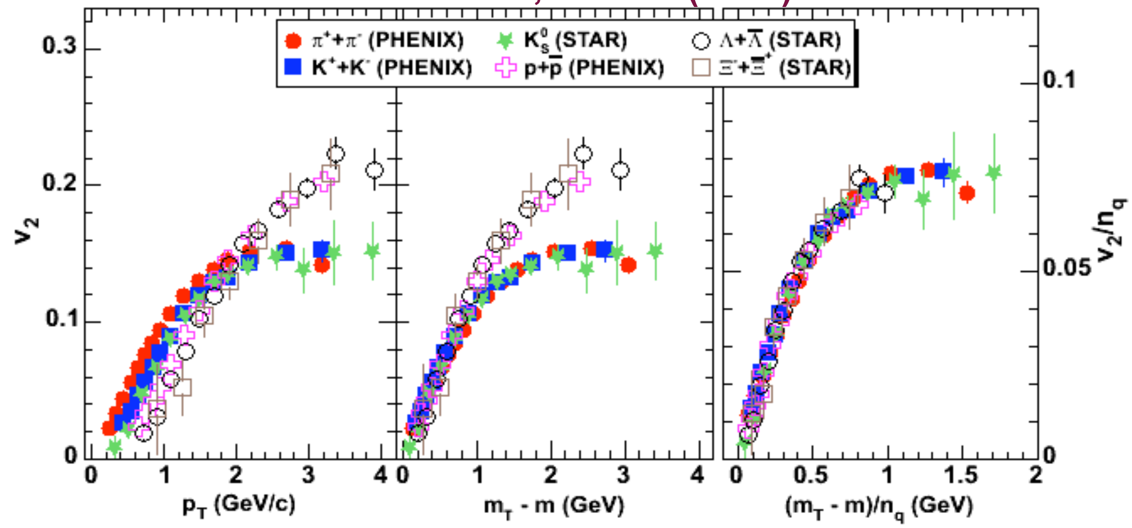
A. Taranenko, QM2009

- Detailed v_2 and v_4 measurements as a function of p_T and centrality have been obtained
- Large data sample (~3.6B events) and good reaction-plane resolution

Scaling properties of v_2



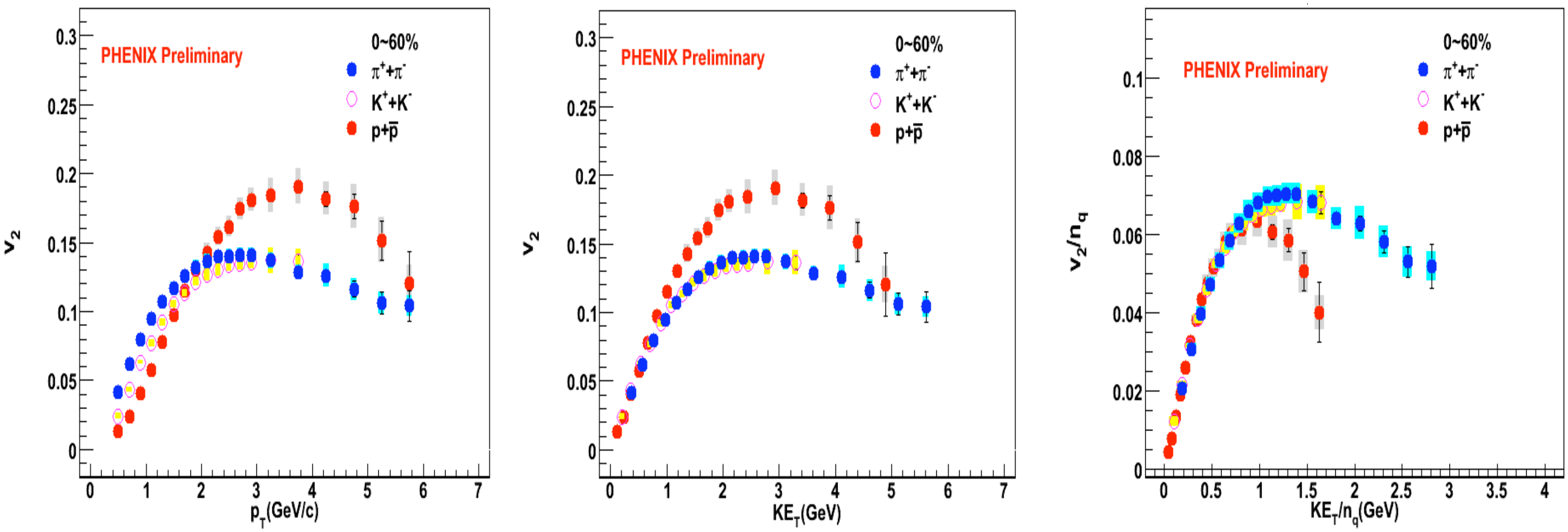
PRL. 98, 162301 (2007)



$KE_T = m_T - m_0$

- At low p_T < ~2 GeV/c, v_2 agrees well with hydrodynamical models and is observed to scale with KE_T up to KE_T ~ 1 GeV (Note: Pressure α Kinetic energy density)
- At intermediate p_T, v_2 can be described by recombination models with number of constituent quark (NCQ) scaling of v_2 -> bulk matter collectivity develops in the pre-hadronic stage
- At which p_T does the scaling break?

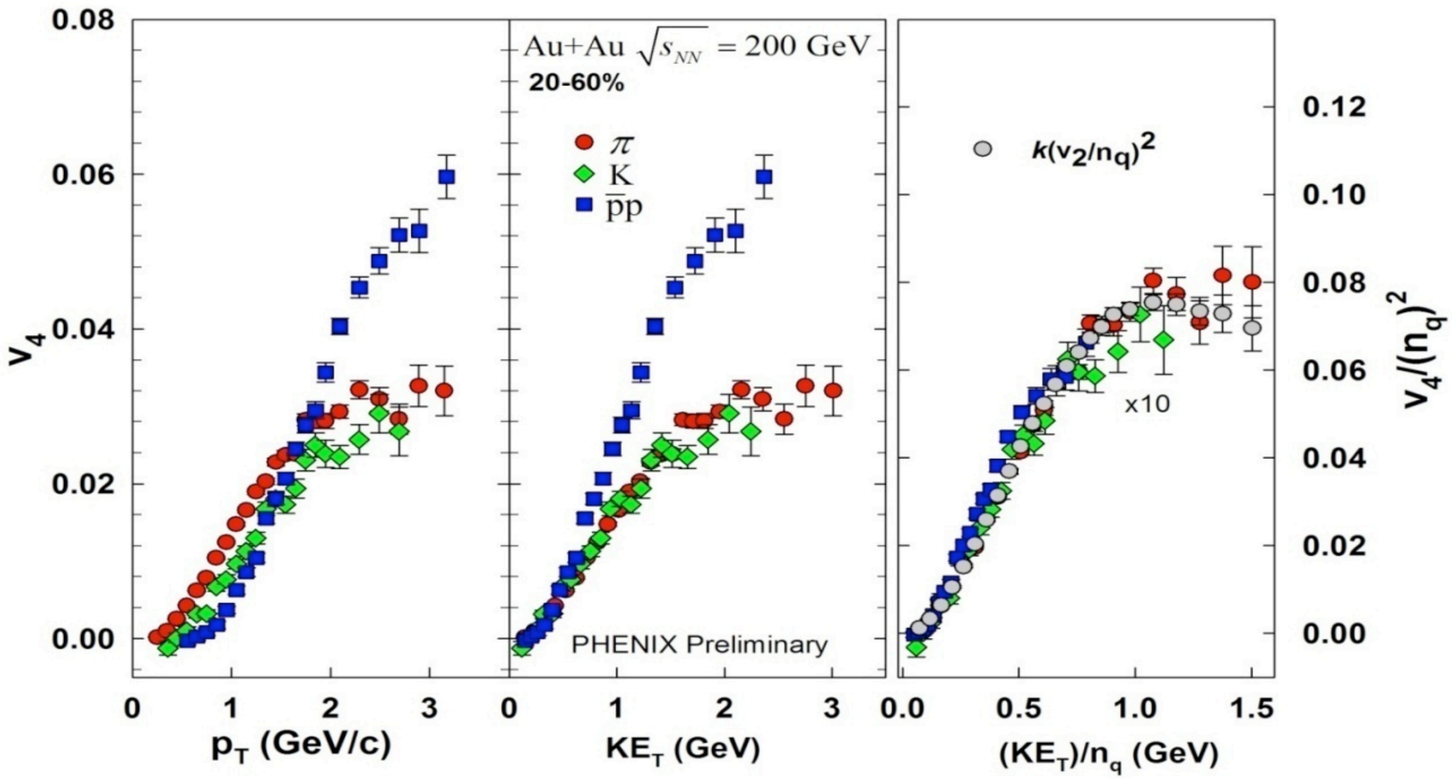
Range of validity of NCQ scaling



S. Huang, QM2008

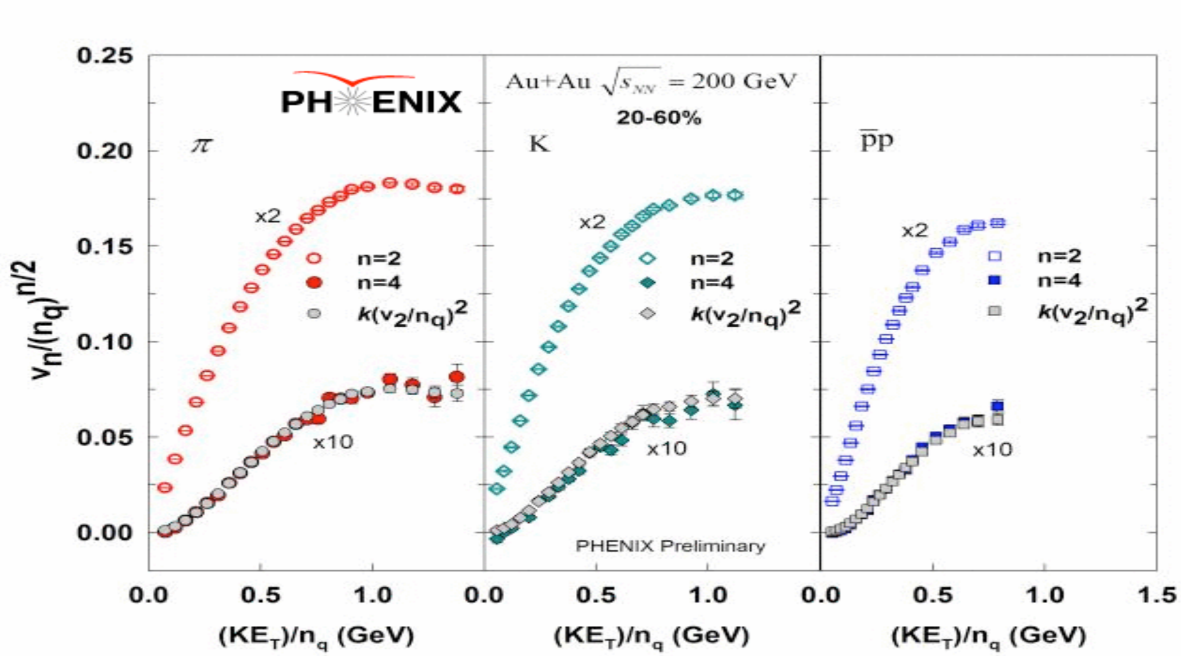
- New ToFW detector extends PID up to p_T ~ 6GeV/c, enables study of validity of NCQ scaling at intermediate p_T
- NCQ scaling is observed to break at KE_T/n_q ~1GeV.
- Possible reasons: different mechanism of recombination for pions and protons at intermediate p_T, influence of non-flow

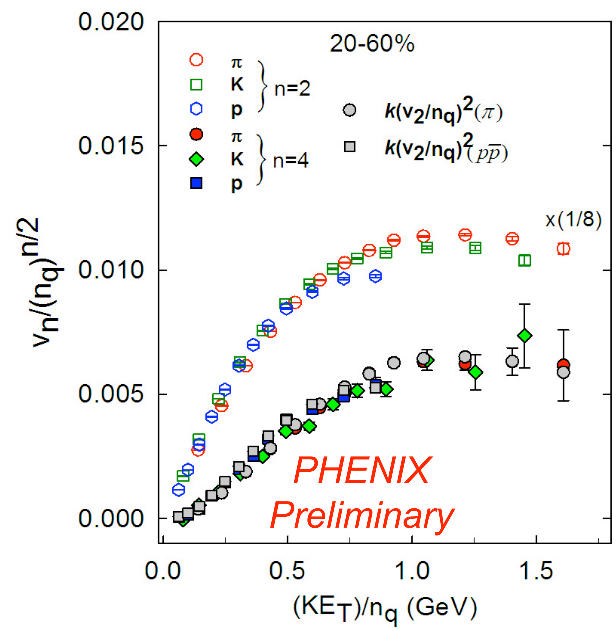
KE_T and NCQ scaling for v_4



KE_T and subsequent NCQ scaling also observed for v_4

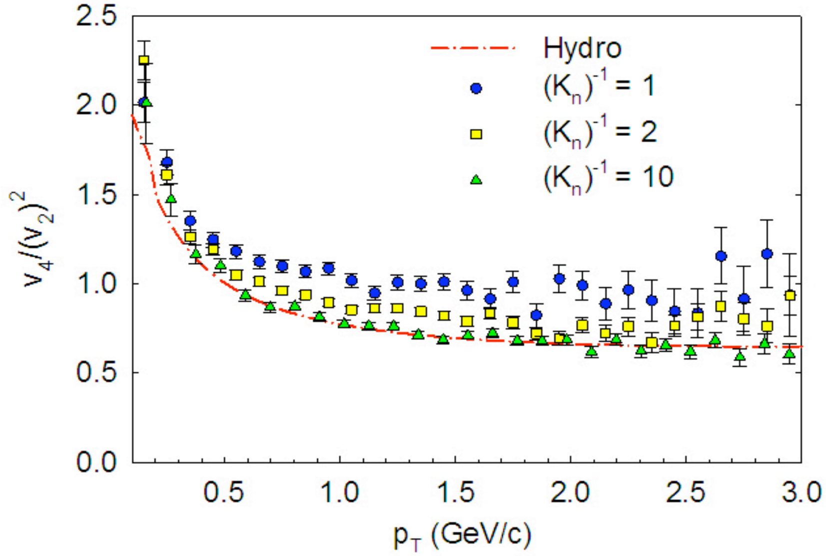
v_4/v_2^2 for different particle species



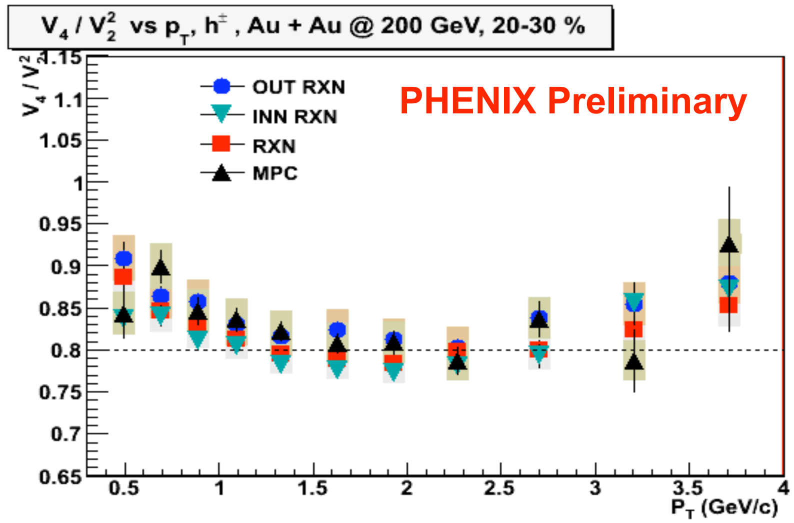


- It has been argued that the ratio v_4/v_2^2 can be used to determine departure from ideal fluid behavior (Borghini, Ollitrault PLB 642 (2006))
- $v_4 = k(v_2)^2$, where k is the same for different particle species
- Baryon and meson v_2 and v_4 scale to the same curve when scaled by n_q and n_q^2 respectively and plotted as function of KE_T/n_q

Comparison of v_4/v_2^2 with hydrodynamic calculations



Numerical 3D hydro calculations (Gombeaud and Ollitrault)

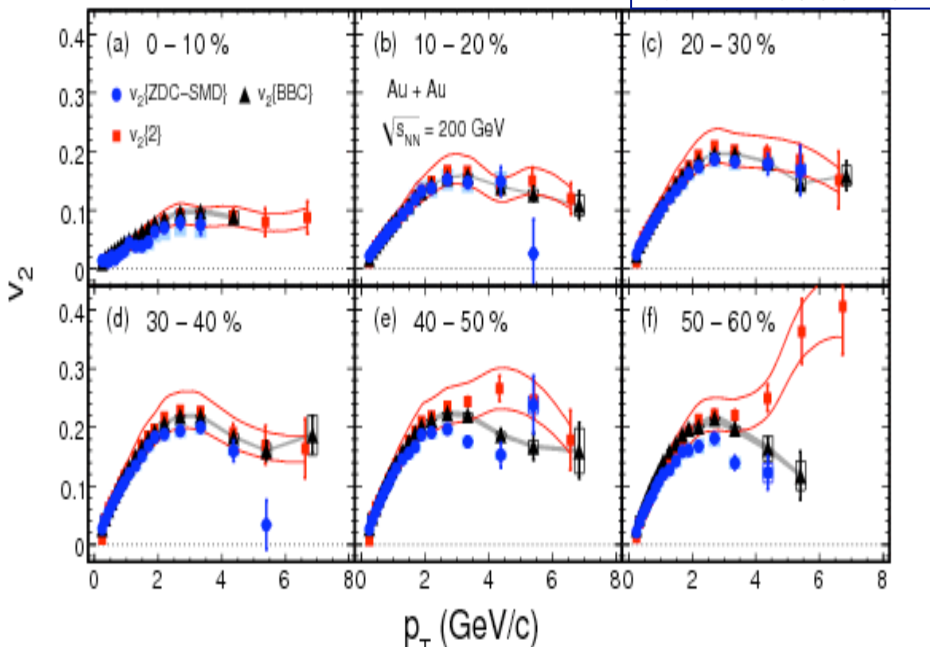


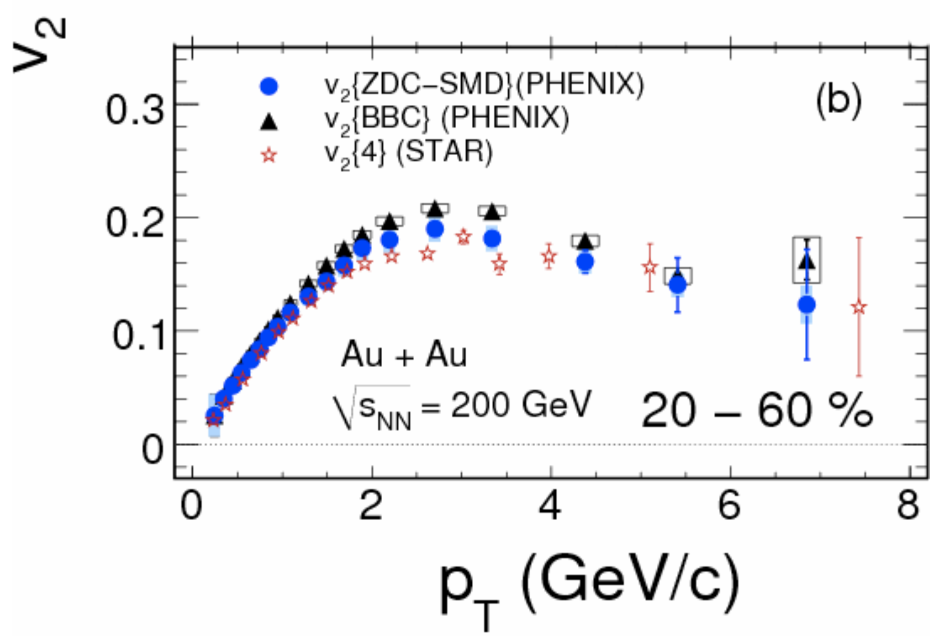
- Predicted value for hydrodynamic behavior and local equilibrium: $v_4/v_2^2 \sim 0.66$
- Knudsen number $K_n \equiv \lambda/L$, λ: mean free path, L: characteristic length
- K_n small => fluid viscosity small
- Comparison of data and model can help to assess the degree of thermalization
- Can extract K_n and hence η/s:

$$\frac{\eta}{s} \sim \lambda T c_s \equiv K_n (RT) c_s$$

Non-flow effects: cumulant vs event plane v_2

arXiv: 0905.1070 [nucl-ex]





- Non-flow correlations: correlations which do not depend on the reaction plane orientation
- Cumulant (second order) v_2 has maximum sensitivity to non-flow, differs from v_2 from event plane
- v_2\{ZDC-SMD\} comparable with v_2\{4\} from STAR, even more so at high p_T
- Wide rapidity gap $|\eta| \sim 6$ from midrapidity for ZDC/SMD and $|\eta| \sim 3 - 4$ at the BBC: non-flow correlations are small (arXiv: 0801.4545v1[nucl-ex])
- ZDC/SMD measures spectator neutrons, event-by-event fluctuations in nucleon positions are small : hence v_2 fluctuations are negligible
- BBC and ZDC/SMD measure v_2 with minimal influence from non-flow and fluctuations

Jets as a probe of the medium: jet tomography

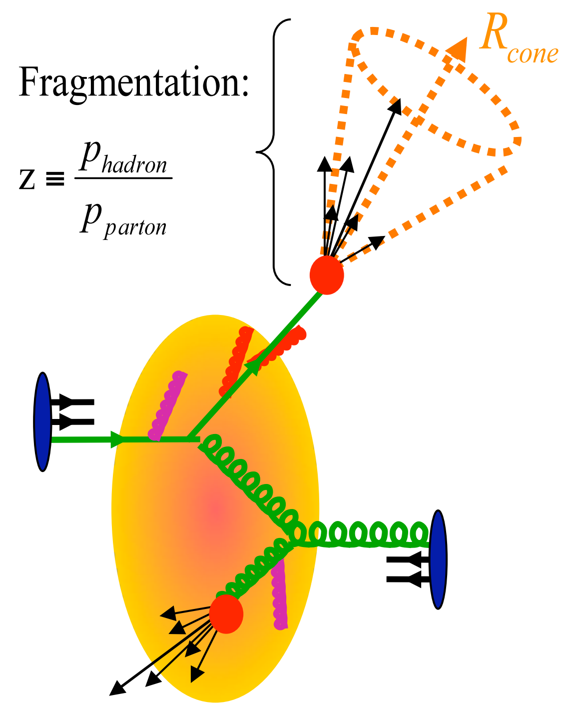
- In relativistic heavy-ion collisions, hard parton-parton interactions occur early

- Scattered partons propagate through the medium radiating gluons and interacting with the medium, thereby losing energy

- Pertinent questions are:

Where does the energy go and how does the medium respond to the energy loss?

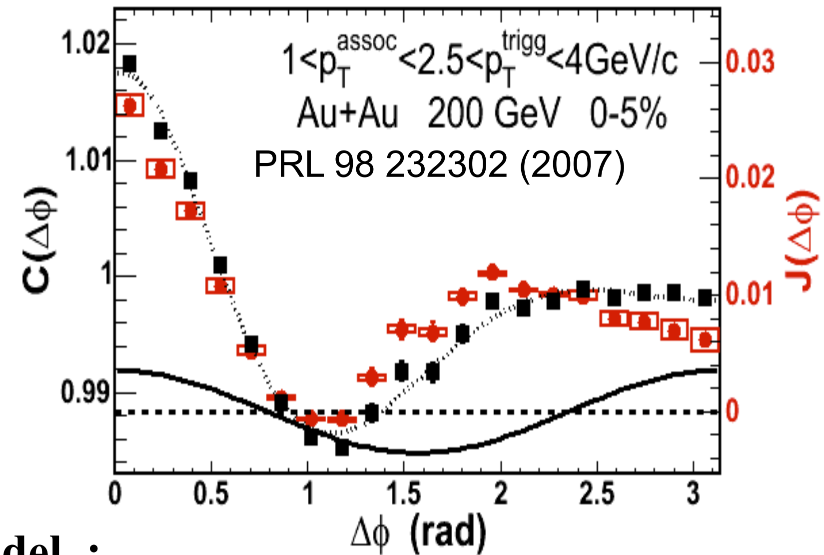
- Partons then fragment into jets, (possibly) outside the medium



Extracting the jet function

Correlation Function

$$C(\Delta\phi) = \frac{N_{Real}(\Delta\phi)}{N_{mix}(\Delta\phi)}$$



Two source model :

$$\underset{Correlation}{C(\Delta\phi)} = a_0 \left[\underset{Flow}{H(\Delta\phi)} + \underset{Jet}{J(\Delta\phi)} \right]$$

Extraction of J(Δφ) requires careful subtraction of the flow contribution (eg. using the ZYAM method)

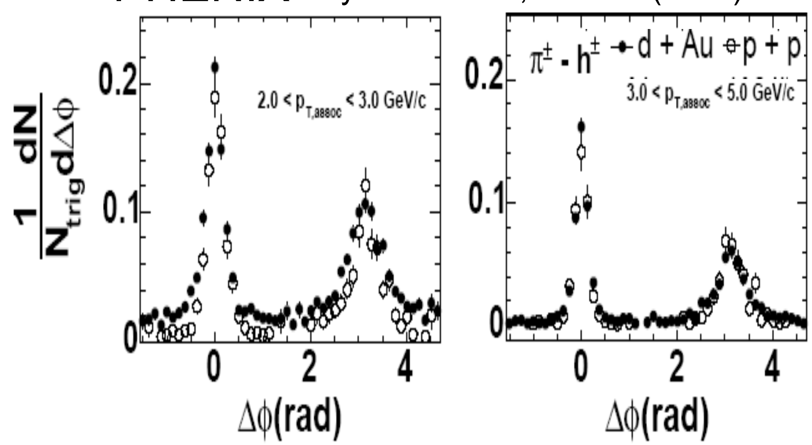
ZYAM : Zero Yield At Minimum

$$J(\Delta\phi_{\min}) = 0 \longrightarrow \textbf{Sets } a_0$$

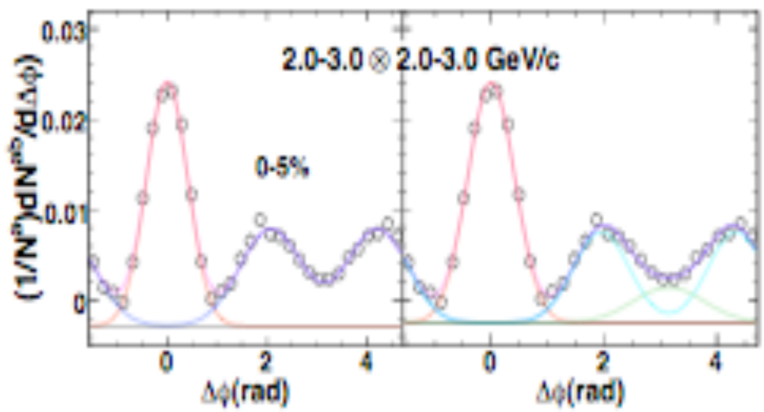
Two-particle azimuthal correlations in p+p and Au+Au

- in p+p collisions, the correlation function exhibits one away-side peak

PHENIX Phys. Rev. C73, 054903 (2006)

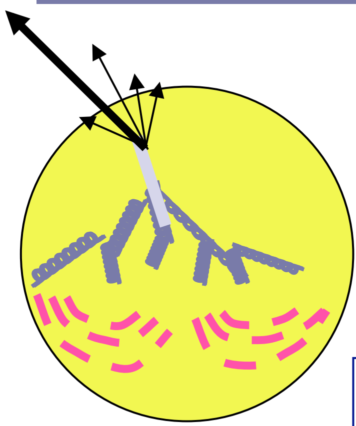


- in Au+Au, double peaked away-side apparent

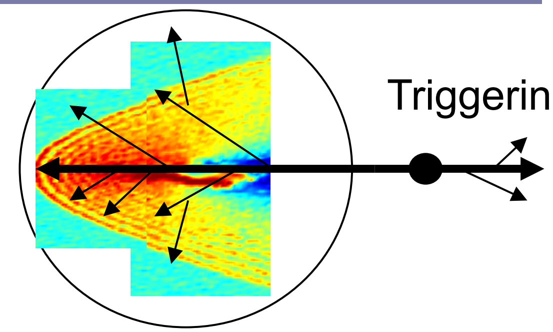


- Double away-side peak structure can be studied in detail to investigate how partons lose energy and how the medium responds

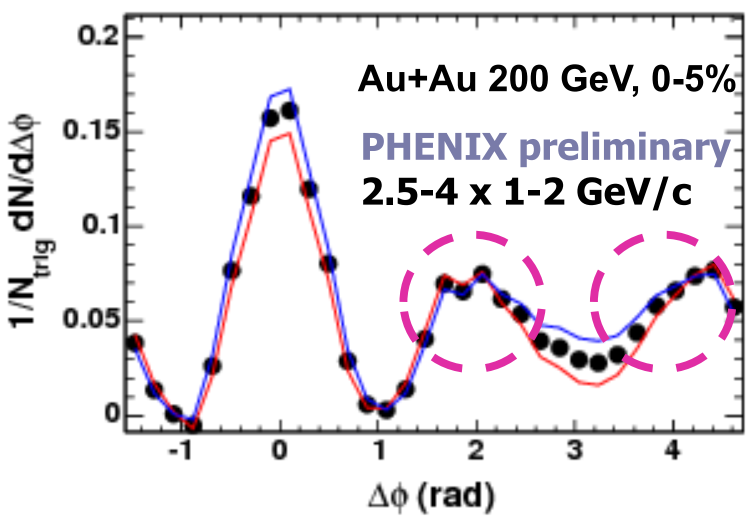
Medium response to jets



Some of the theoretical models describing the away-side structure:



J. Jia



- Strong away-side modification observed at intermediate p_T in heavy-ion collisions
- Interaction of jets with the medium

- Wake effect or sonic boom -> measure sound speed

$$\cos\theta = \frac{c_s}{c}$$

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

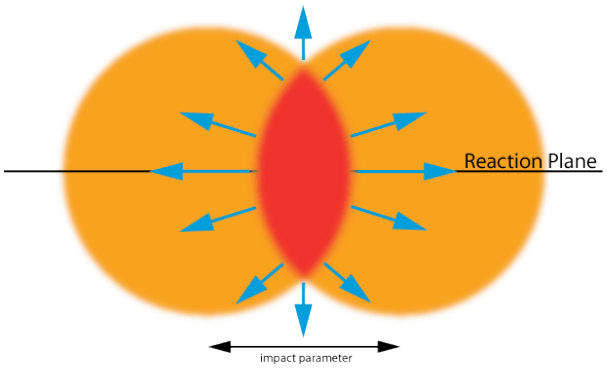
- Interaction of jet with the underlying flow field

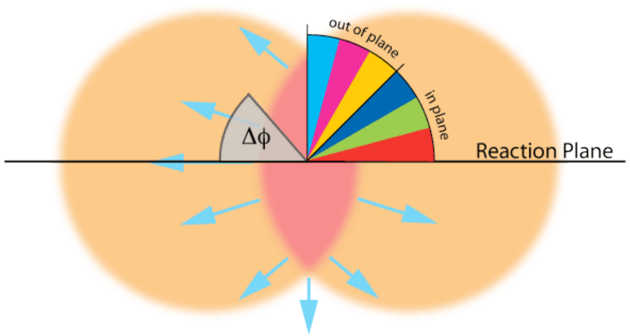
Armesto,Salgado,Wiedemann, PRC 72 (2005) 064910

- Cerenkov gluon radiation

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

Controlling path length effects





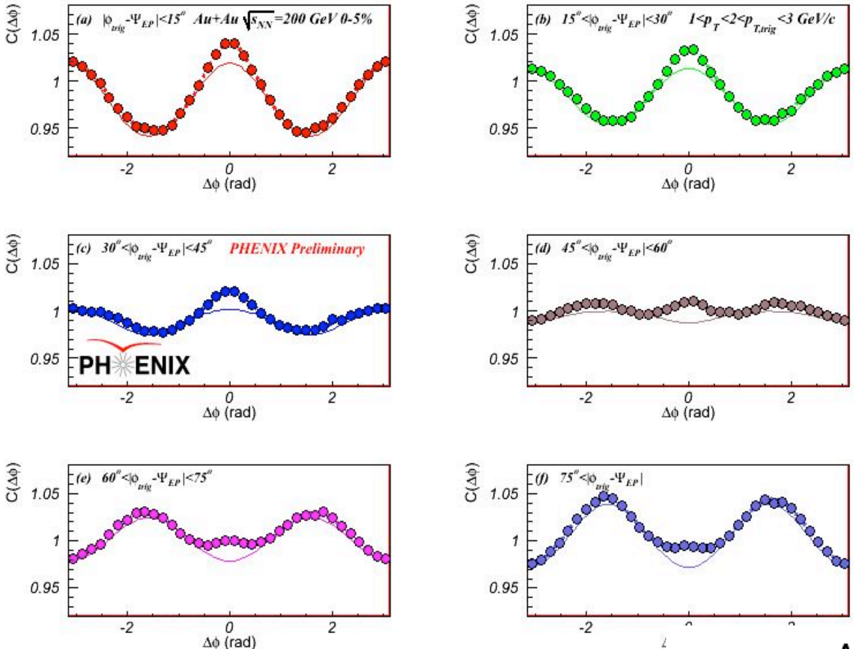
- Centrality controls the geometry and the energy density

$$\varepsilon_{Bj} = \frac{1}{\pi R^2}\frac{1}{\tau_0}\frac{dE_T}{dy}$$

- The orientation of the trigger particle w.r.t the reaction plane constrains the path length of the jet and hence its energy loss

- Varying both centrality and trigger orientation can serve to disentangle the jet energy loss and medium response

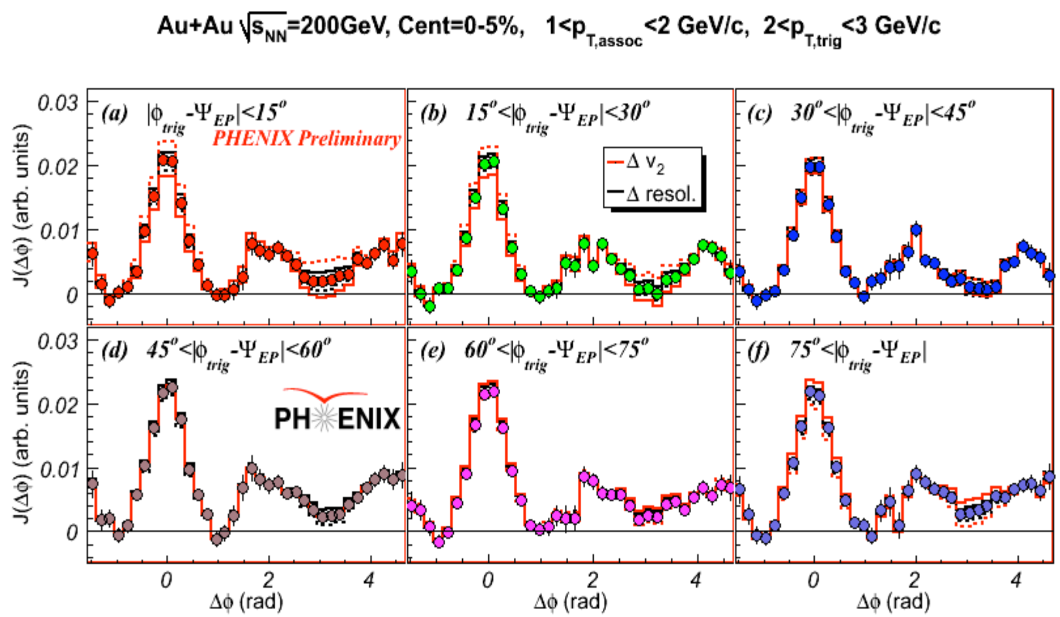
Correlation and Jet functions in Au+Au collisions



Correlation functions

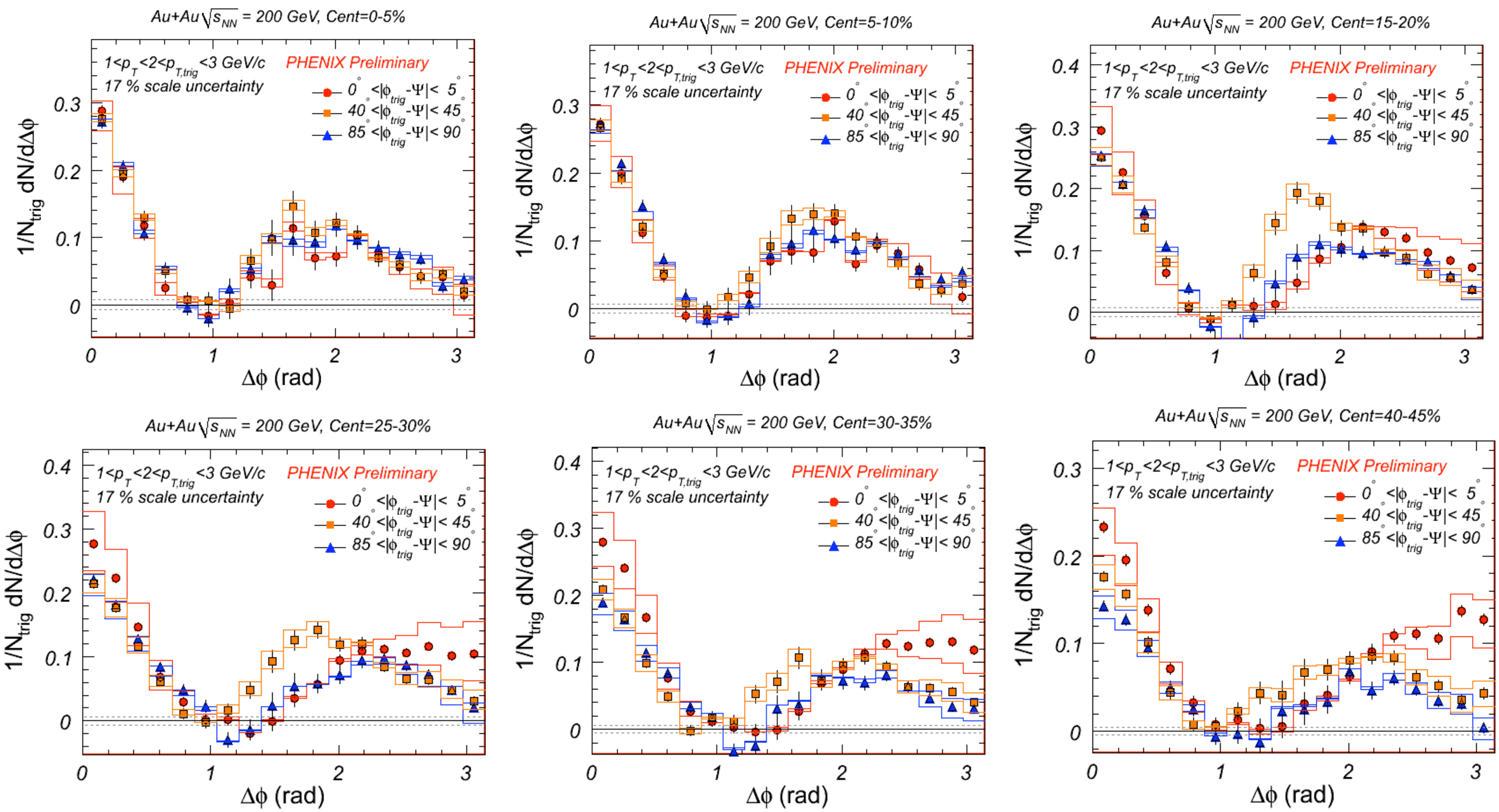
Au+Au √s=200 GeV, 0-5% Centrality

Jet functions



- Jet functions similar for different trigger orientations: little path length dependence in central collisions

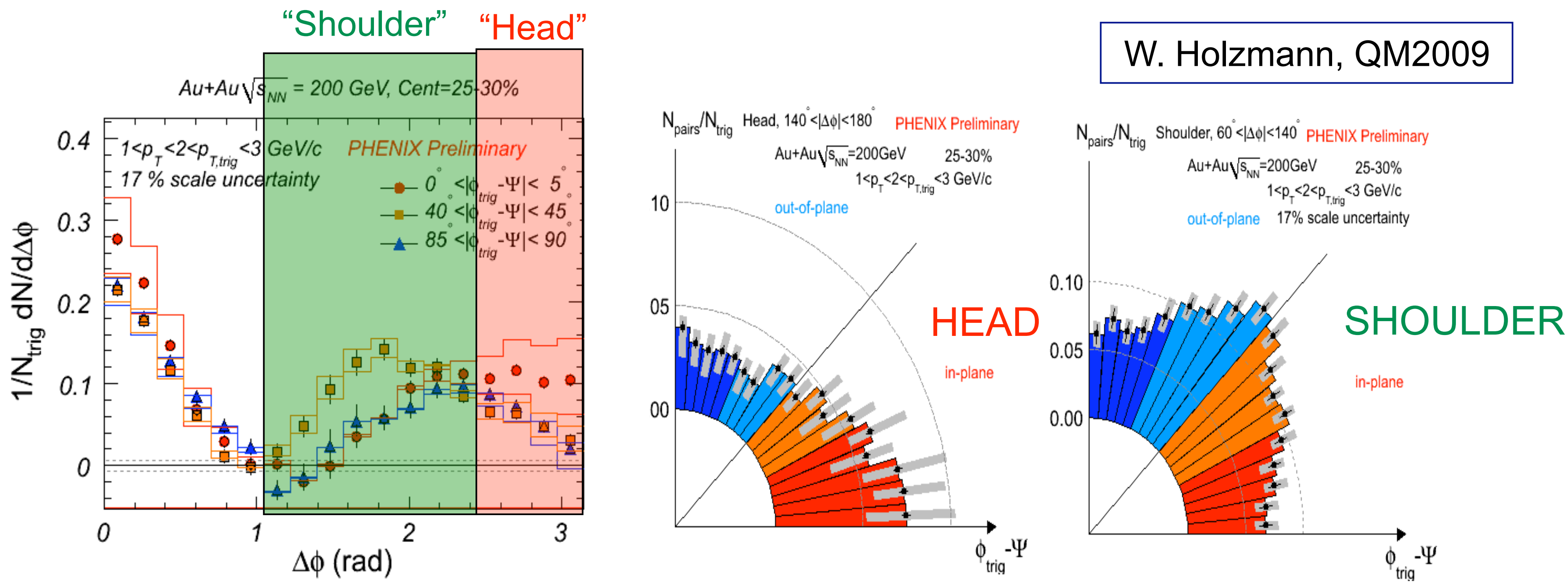
Evolution of away-side peak with centrality



W. Holzmann, QM2009

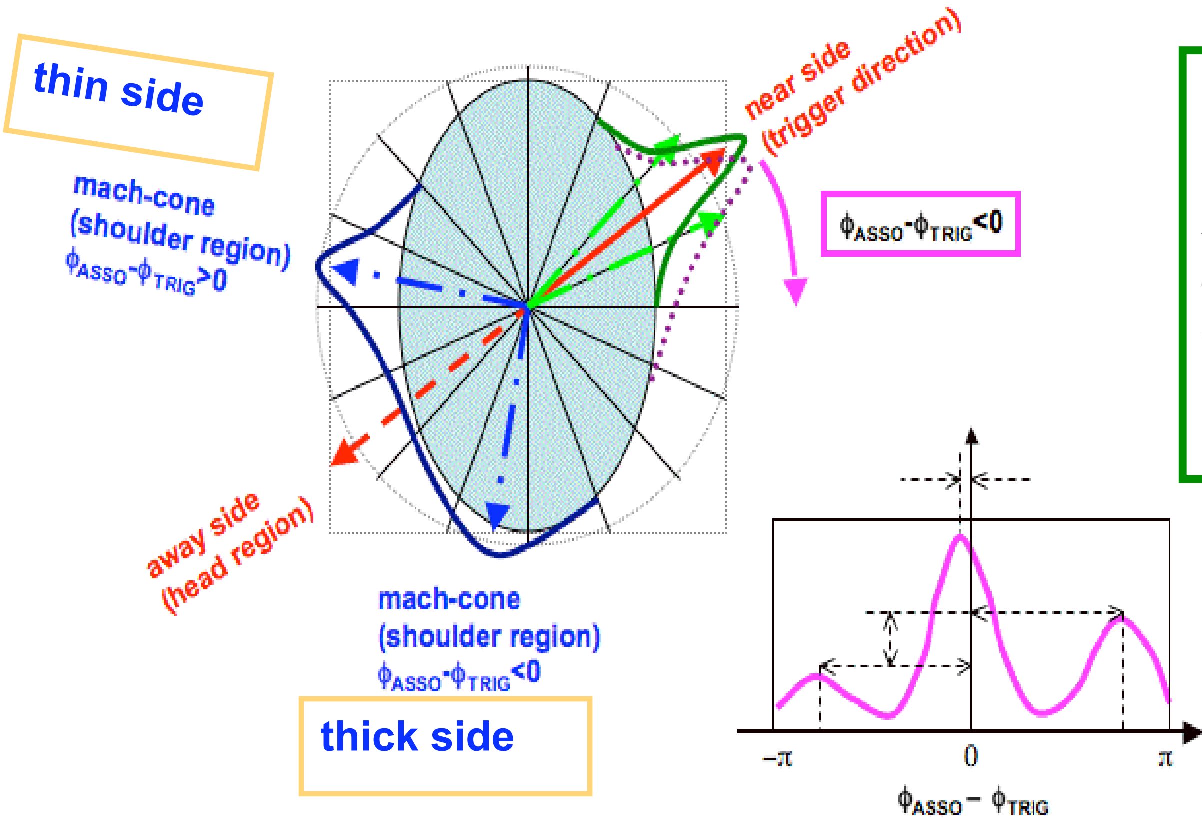
Reaction-plane dependent correlations consistent with additional contribution at π/2 and/or with a moving peak postion

Comparison between "Head" and "Shoulder" yields



- Two particle correlations relative to the event plane show a geometry dependent change in yield of the away-side peak
- Two regions can be identified: "Head": $2.5 < |\Delta\varphi| < 3.1$, "Shoulder": $1.0 < |\Delta\varphi| < 2.5$
- Geometry dependence of "Head" region consistent with energy loss scenario
- "Shoulder" region shows a very different geometry dependence from "Head" region
- Indicative of separate physics, can be attributed to medium response

Unfolded distributions: more differential control of path length



If the trigger angle is fixed around +/−(π/4), the associate particles emitted left or right w.r.t. trigger direction would feel the different thickness of the almond. It is because the almond shaped medium is asymmetric w.r.t. jet axis.

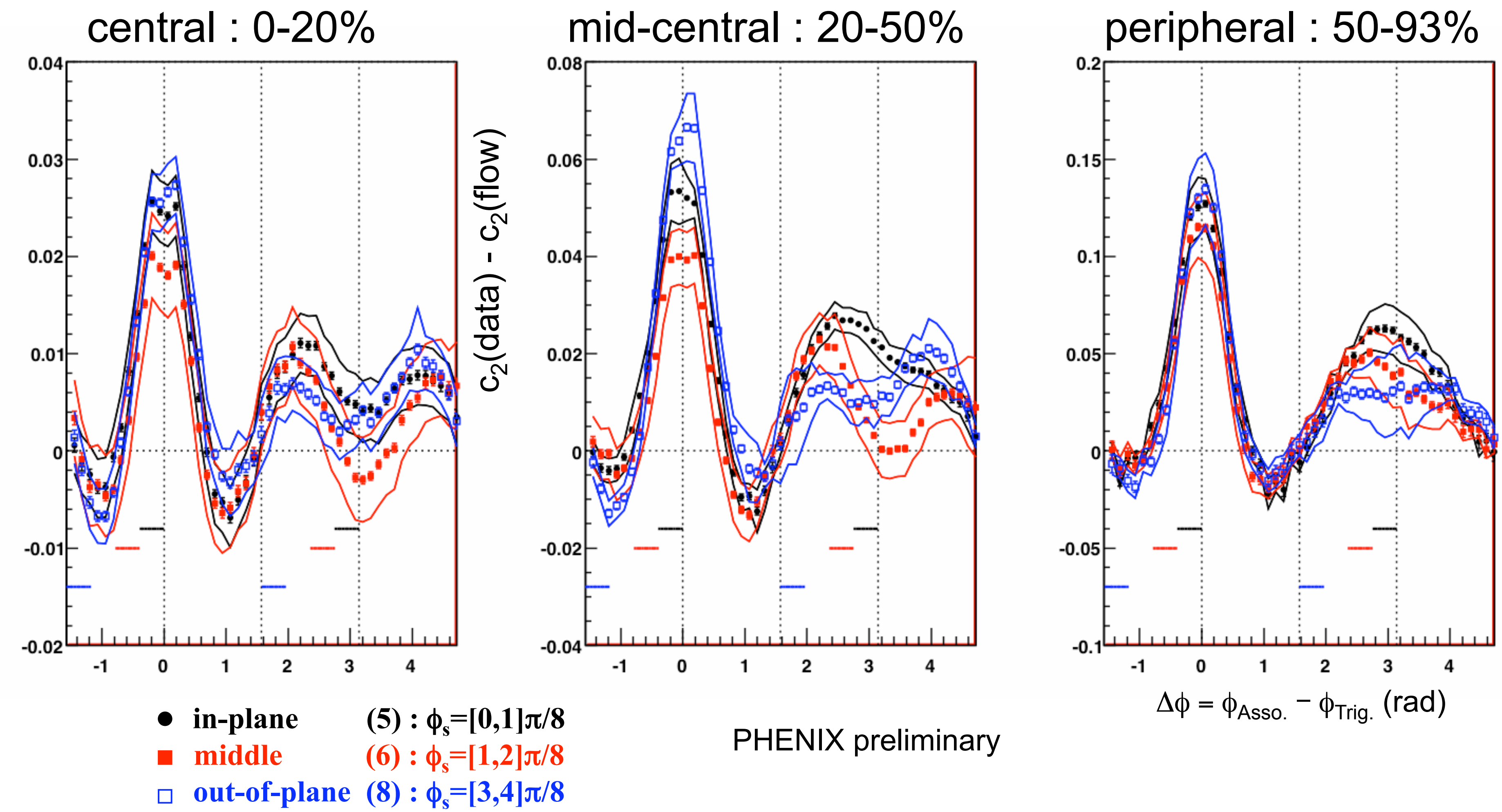
Given the level of path dependence already seen, path length differences due to left/right asymmetry should also be observed

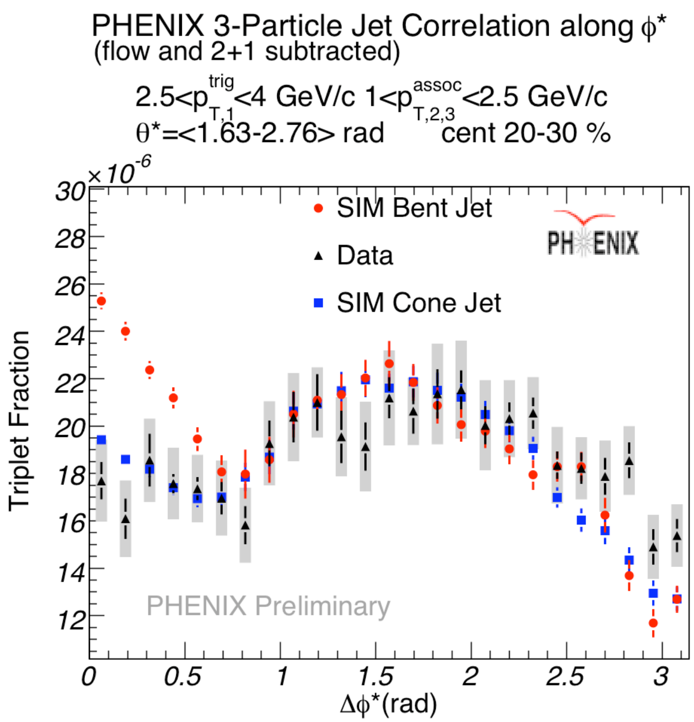
Left/Right asymmetries observed in di-hadron correlations

200GeV Au+Au -> h-h (run7)

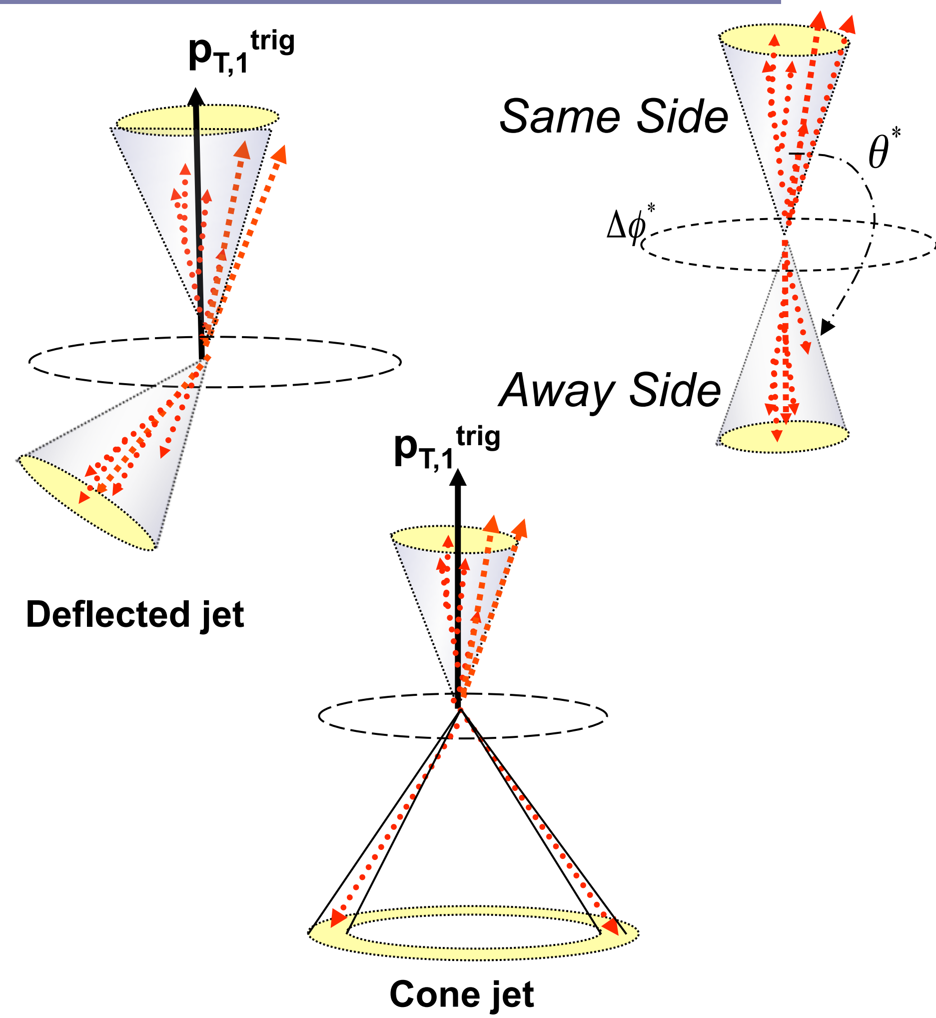
(p_T^{Trig}=2~4GeV/c, p_T^{Asso}=1~2GeV/c)

S. Esumi





$$\Delta\phi^{*} = \phi^{*}_{12} - \phi^{*}_{13}$$



- Measured three particle correlations are consistent with cone-like emission
- Caveat: does not exclude other contributions to the 3-particle correlation

Summary

- Detailed v_2 and v_4 measurements performed by PHENIX

- Demonstration of n_q and n_q^2 scaling for v_2 and v_4 respectively: v_4 exhibits the same scaling patterns as v_2

- Extraction of transport properties of the medium now possible with wealth of data on differential harmonic flow (centrality, p_T, particle species…), currently under way

- Two-particle correlations relative to the reaction plane studied in great detail in small centrality bins and small angles w.r.t the reaction plane and also in terms of left/right asymmetry

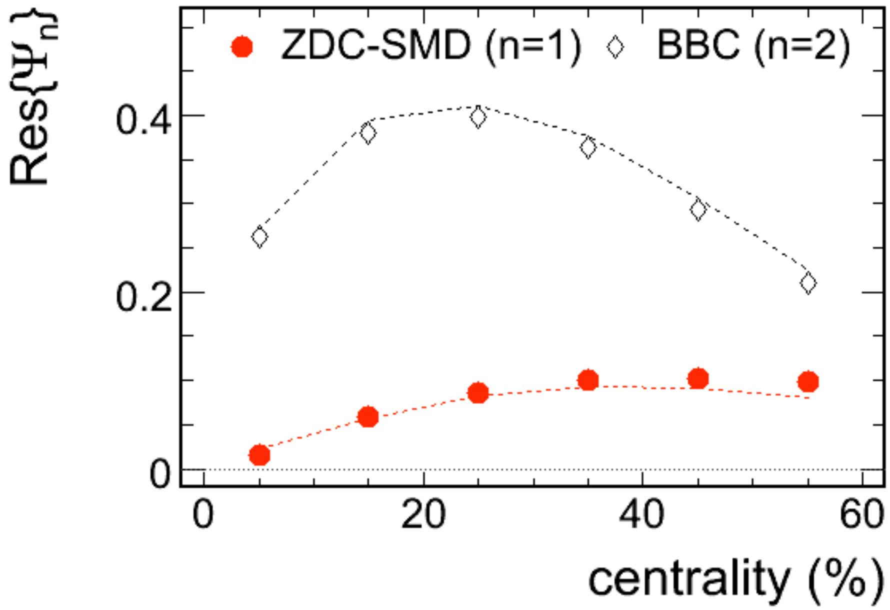
- Three particle correlations suggest a cone-like emission on the away-side

- A lot of results not covered (for e.g flow/correlations in Cu+Cu, high p_T correlations)

- More developments to come!

BACKUP

H. Masui, HQ2008



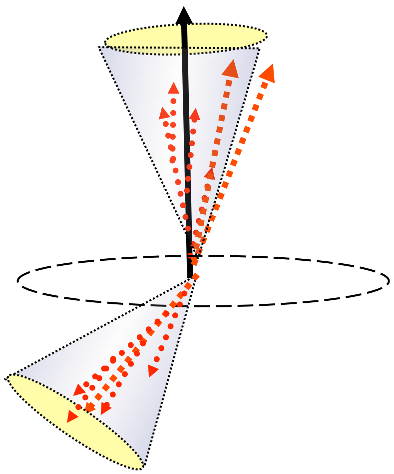
$$v_2 = \frac{v_2^{obs}}{\mathrm{Res}\{\Psi_n\}} = \frac{\langle \cos(2[\phi - \Psi_n]) \rangle}{\langle \cos(2[\Psi_n - \Psi_{\mathrm{RP}}]) \rangle}$$

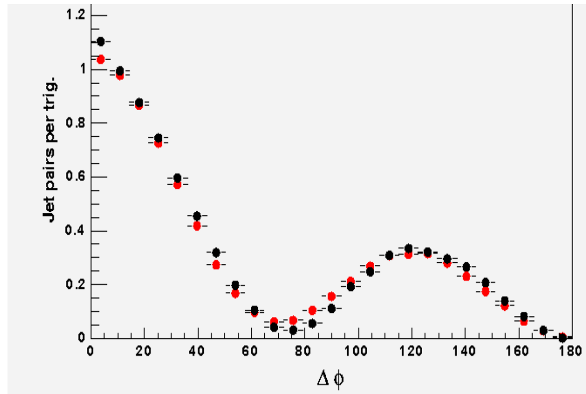
- Backward - Forward (south - north, S - N) correlation (symbols)
- ZDC - BBC - CNT correlation (dashed lines)

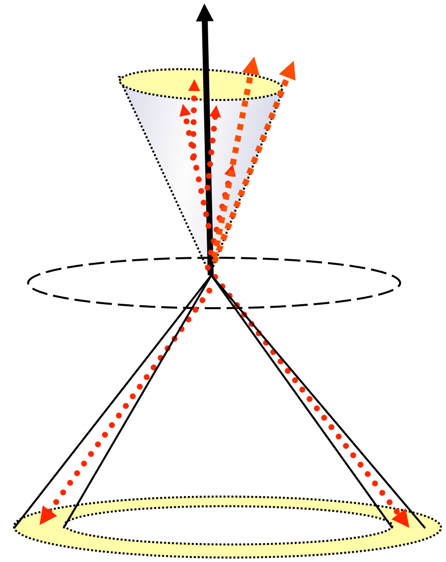
$$\mathrm{Res}\{\Psi_n\} \approx \sqrt{2\,\langle \cos(2[\Psi_n^S - \Psi_n^N]) \rangle}$$

$$\mathrm{Res}\{\Psi_n\} = \sqrt{\langle \cos(2[\Psi_n^B - \Psi_n]) \rangle} \times \sqrt{\frac{\langle \cos(2[\Psi_n - \Psi_n^A]) \rangle}{\langle \cos(2[\Psi_n^A - \Psi_n^B]) \rangle}}$$

Deflected and Cone Jet Simulations





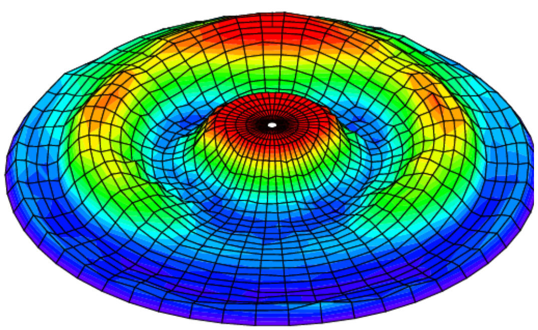


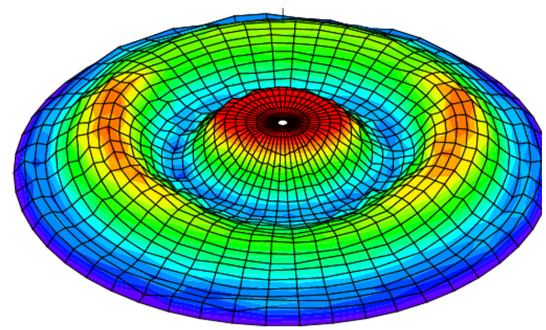
2-particle correlations matched

Deflected jet sim

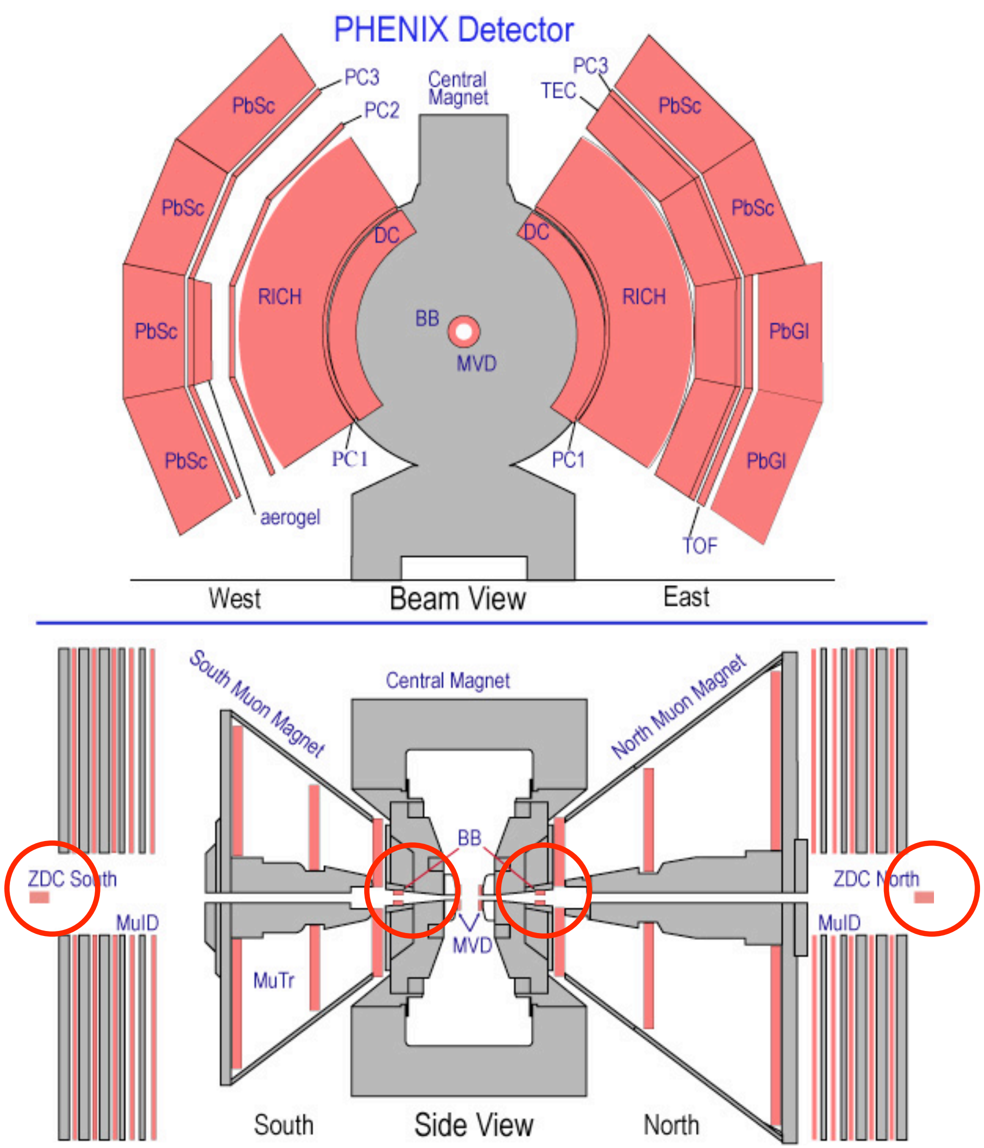
Mach Cone sim

N.N. Ajitanand





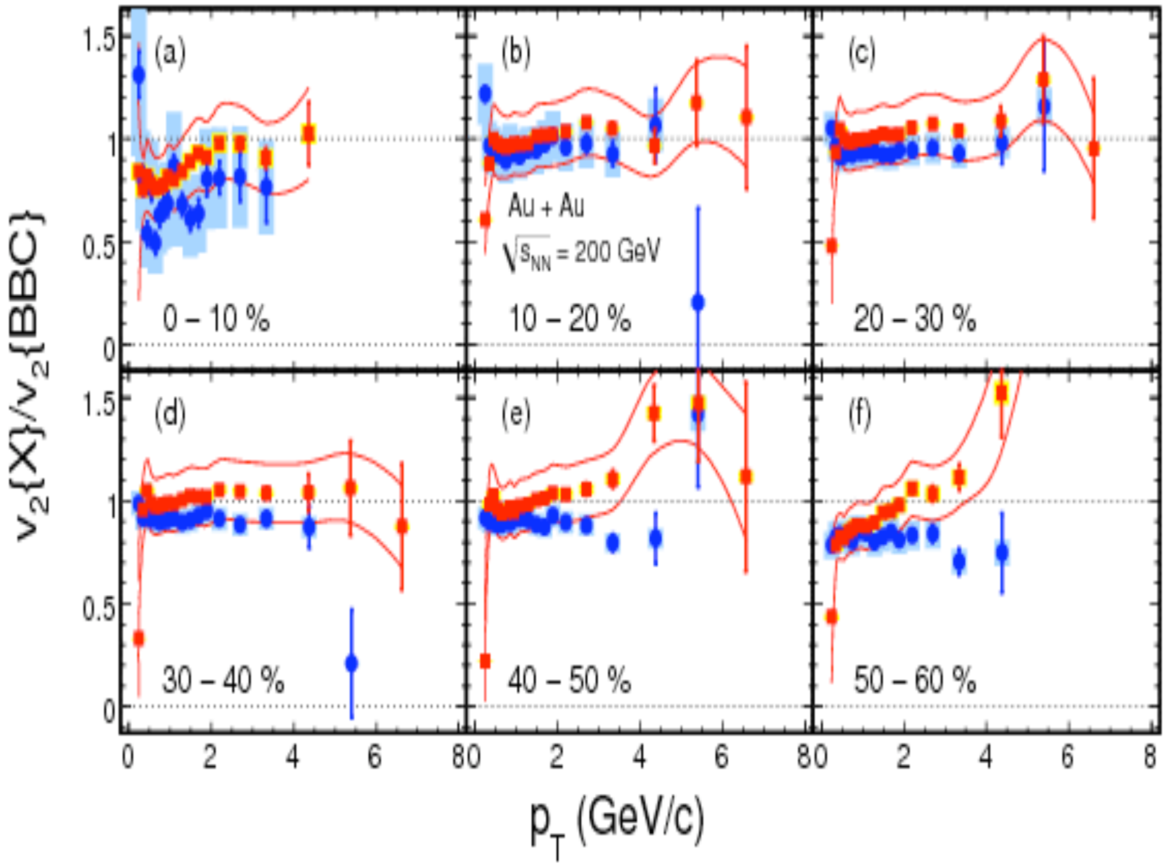
3-Particle di-jet correlations allow a distinction between different mechanistic scenarios !



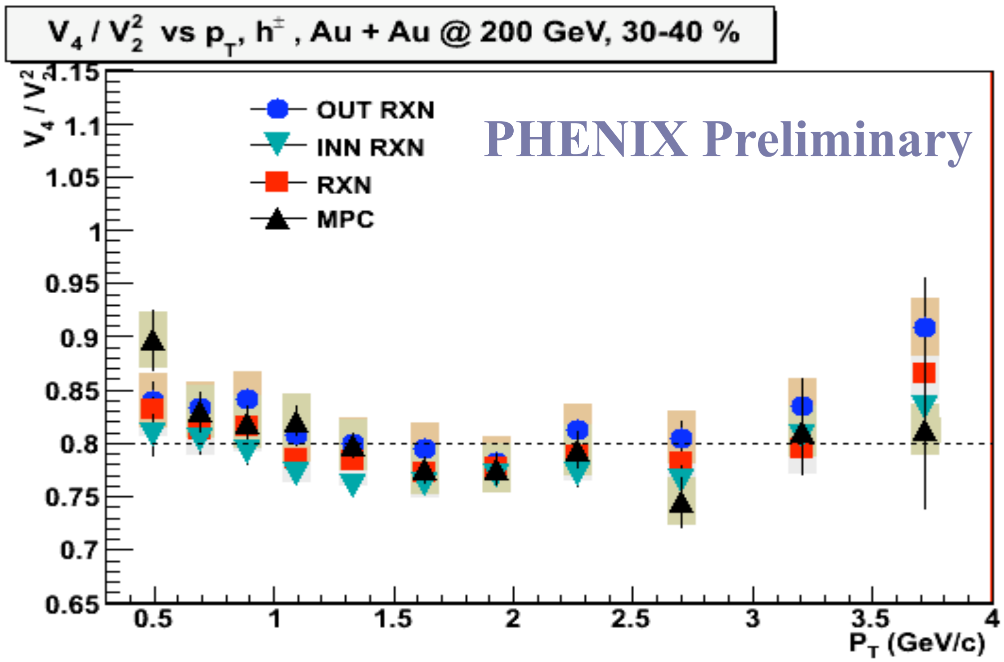
- PHENIX Run 4 Au + Au 200 GeV, ~650 M events
- Trigger, z-vertex, centrality, event plane
  - Beam-Beam Counter (BBC), $|\eta| = 3.1 - 3.9$, full azimuth
  - Zero Degree Calorimeter (ZDC) and Shower Maximum Detector (SMD), $|\eta| > 6$, full azimuth
    - also use the central arm to determine the reference event plane
- Tracking
  - Central arm (CNT), $|\eta| < 0.35$, half of full azimuth
    - E/p > 0.2 to improve S/B ratio at high p_T

Non-flow effects: cumulant vs event-plane v_2

arXiv: 0905.1070 (nucl-ex)



v_4 / v_2^2 for charged hadrons



7/28/09

Arkadij Taranenko, QM2009

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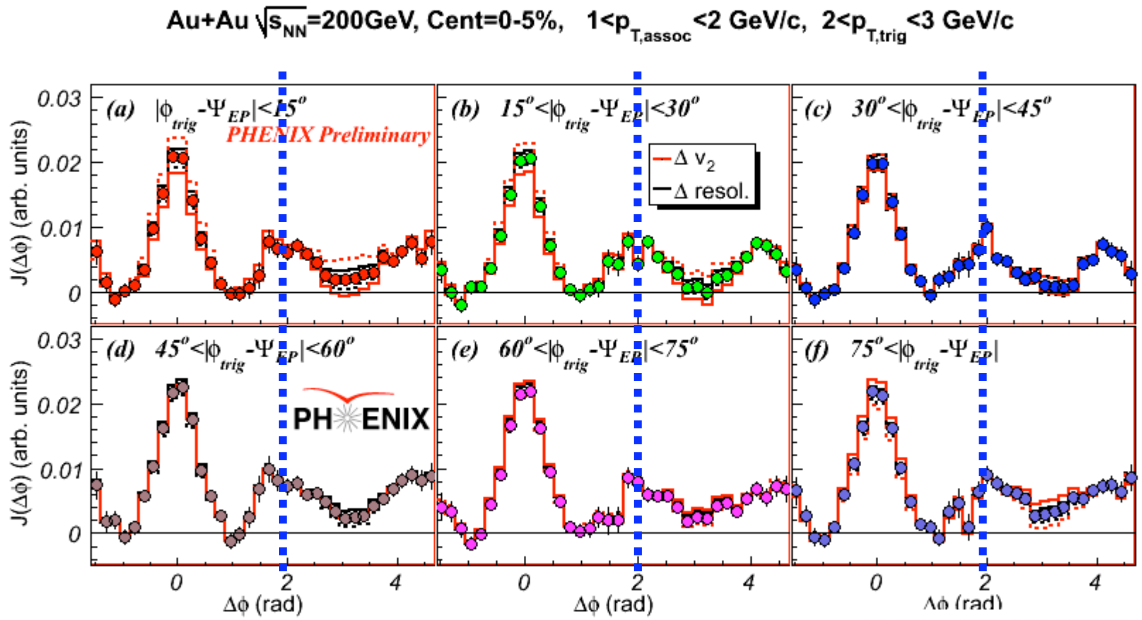
Jet functions for different trigger orientations



0-5 %

30-40 %