What can we learn about the sQPG at RHIC from Azimuthal Angular Correlation Measurements?

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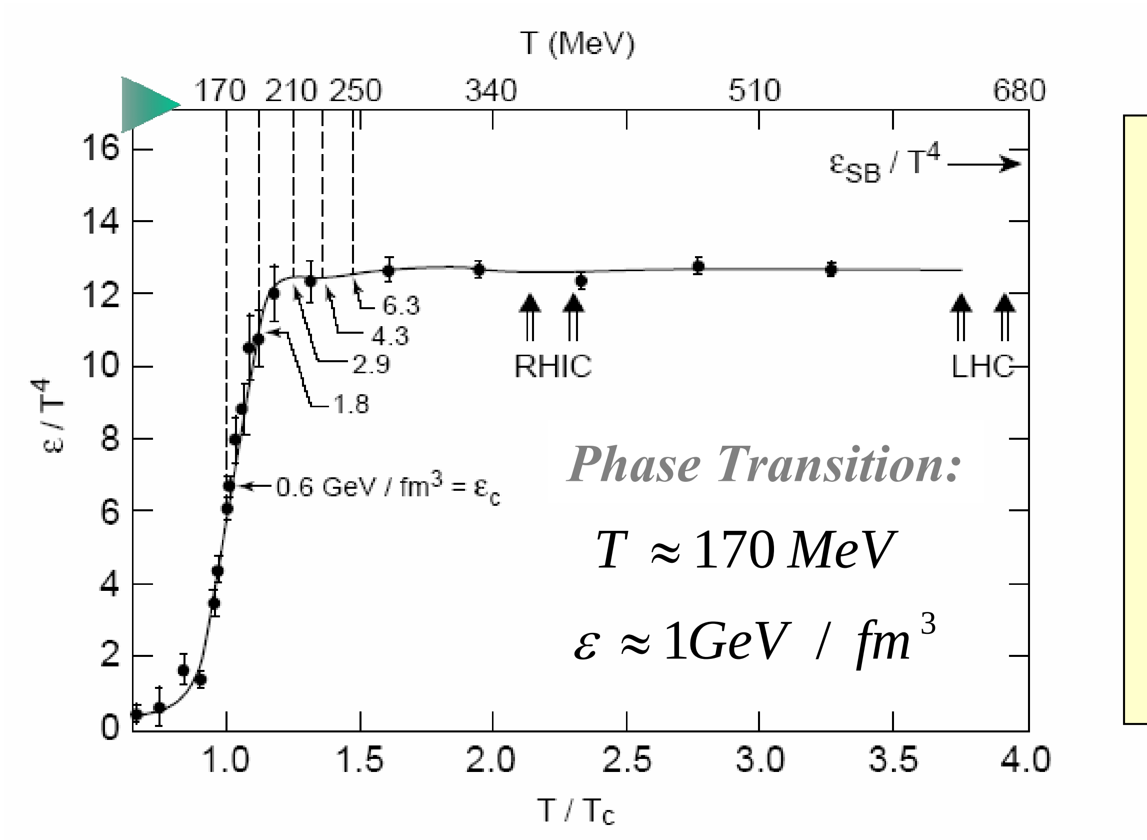
NUCLEAR CHEMISTRY @ STONY BROOK

Motivation

A Cue from Lattice QCD:



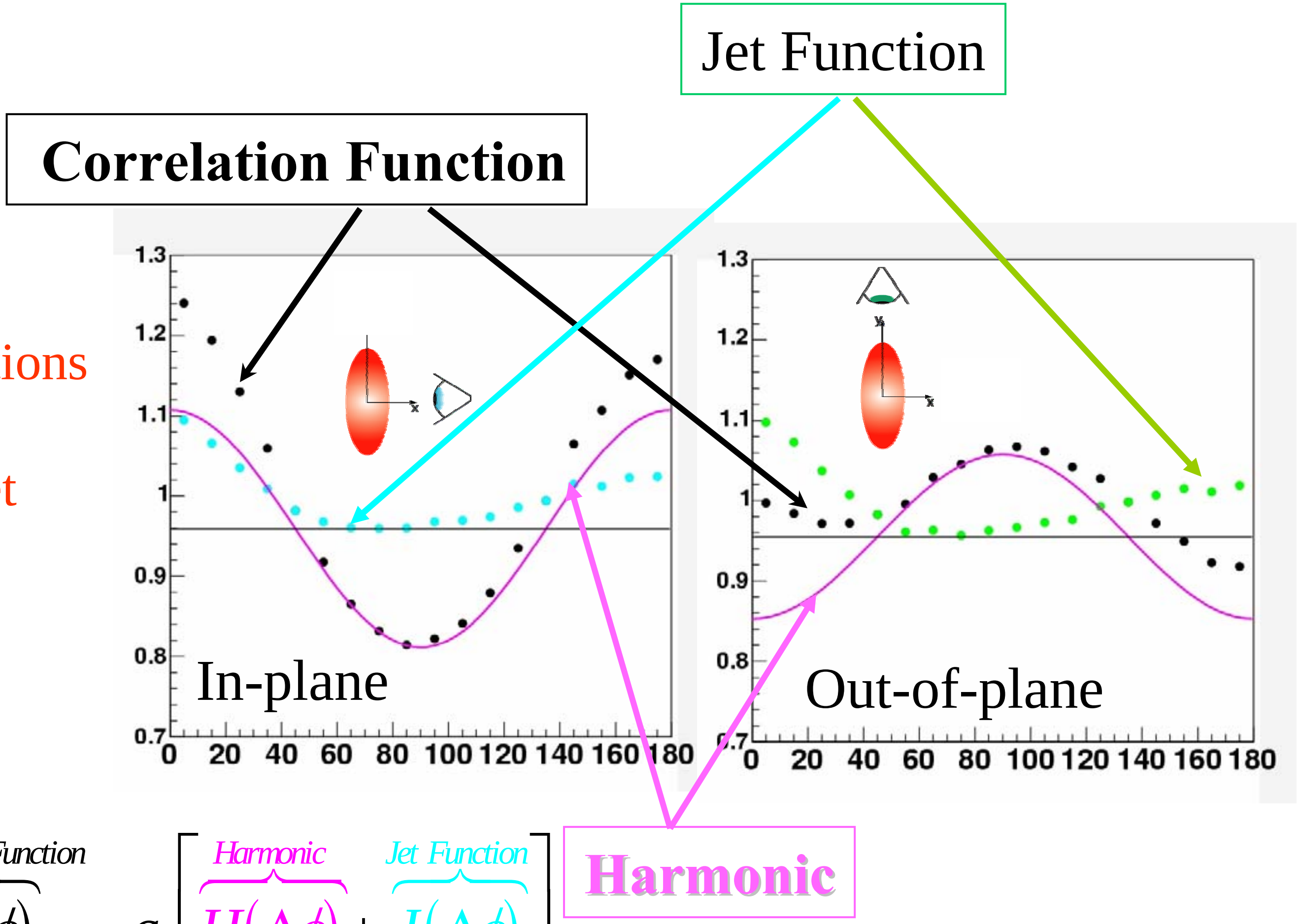
Phase Transition

High energy density thermalized, strongly interacting partonic matter ?

Probes that indicate equilibrated nuclear matter with ε > 1 GeV/fm³ are of particular interest

Why is the correlation probe so compelling?

Azimuthal Correlations are derived from Harmonic and di-jet contributions



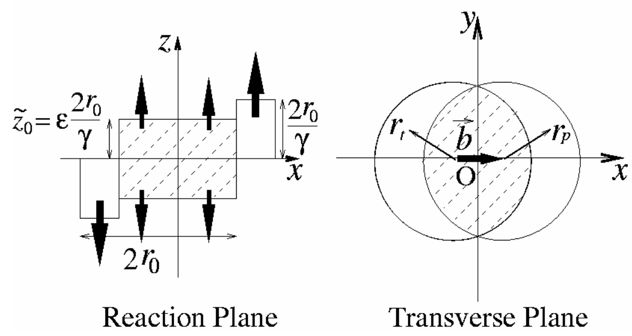
$$\overbrace{C(\Delta\phi)}^{\text{Correlation Function}} = a_0\left[\overbrace{H(\Delta\phi)}^{\text{Harmonic}} + \overbrace{J(\Delta\phi)}^{\text{Jet Function}}\right]$$

Azimuthal Correlations Provide Direct Access to the Properties of the High Energy Density Matter Created at RHIC

What information do correlation measurements provide?

v2:

- ***reliable pressure estimates***
- ***thermalization***
- ***transverse dynamics of the medium***
- ***EOS***



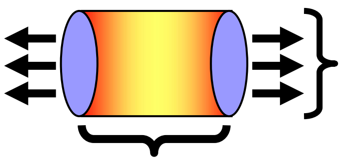
❖ ***A direct route for the study of jets:***

- ***Characterization of Jet Topologies in pp, dA & AA***
  - ***Quantification of Medium Induced Modifications to Topologies***
    - ➔ ***Crucial for study of the properties of the medium***
  - ***Tomographic Imaging of Hot and Dense Partonic Matter***

Simultaneous Study of Harmonic and Jet Correlations is Crucial

High Energy density matter created at RHIC!

Extrapolation From E_T Distributions



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

time to thermalize the system ($\tau_0 \sim 0.2 - 1$ fm/c)

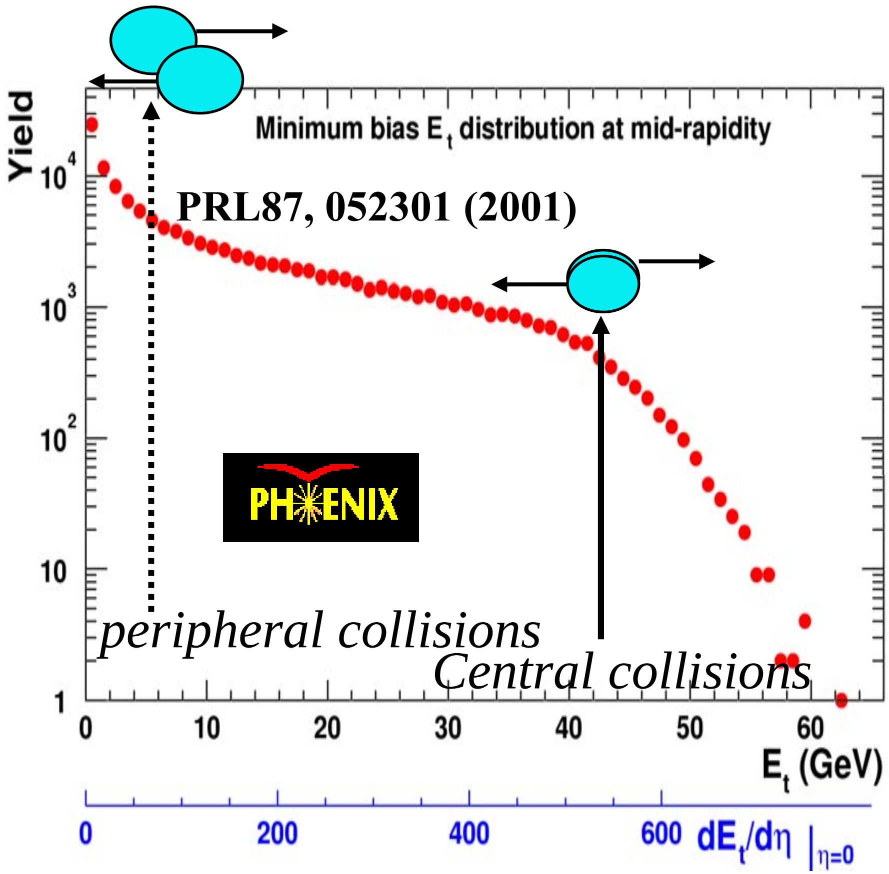
$\varepsilon_{Bjorken} \sim 5 - 15$ GeV/fm^3

$\sim 35 - 100\ \varepsilon_0$

Phase Transition:

$T \approx 170 MeV$

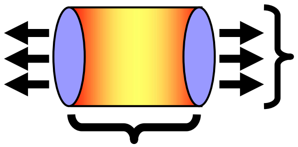
$\varepsilon \approx 1 GeV / fm^3$



The Energy Density is Well Above the Predicted Value for the Phase Transition !

Is the energy thermalized?

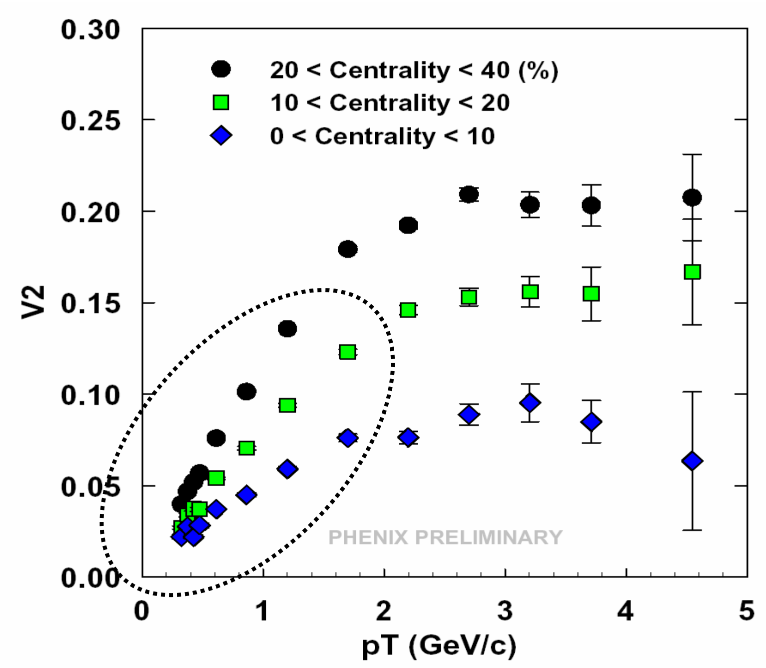
Extrapolation From E_T Distributions

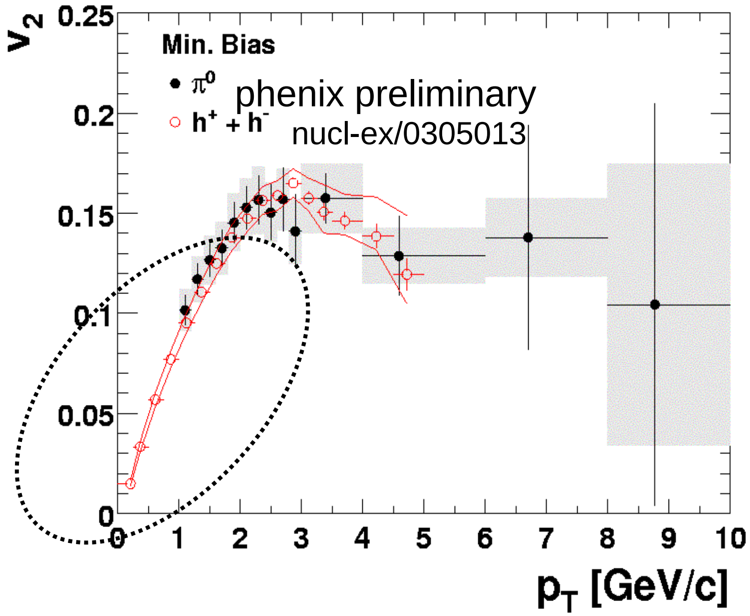


$$\varepsilon_{Bj} = \frac{1}{\pi R^2}\frac{1}{\tau_0}\frac{dE_T}{dy}$$

$$\left(P = \rho^2 \cdot \left(\partial\varepsilon / \partial\rho \right)\Big|_{s/\rho} \right)$$

Pressure ⇨ Flow





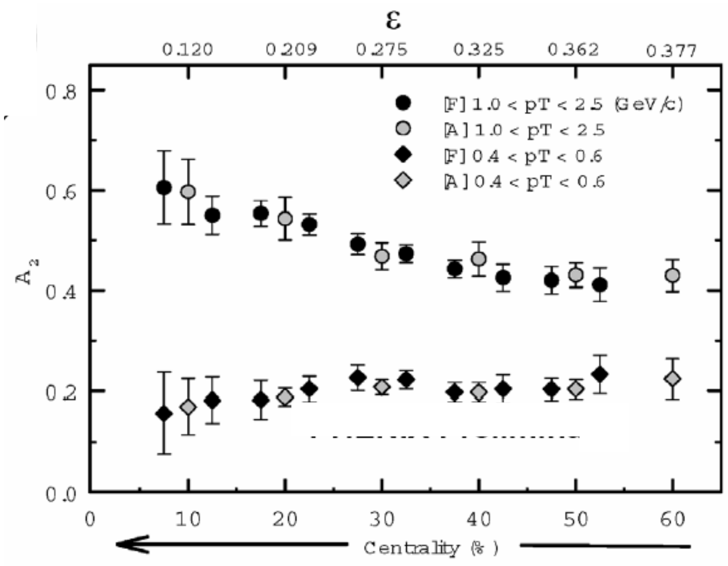
Substantial Signals Attributable to Flow are observed ?

Probing the hydrodynamic origin of v2 via scaling relations

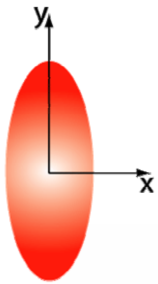
Hydro Limit

$$\frac{v_2}{\varepsilon} \propto \frac{p_T < u_T >}{T} - 1 \qquad p_T u_T >> T$$

$$\frac{v_2}{\varepsilon} \propto \frac{p_T^2 < u_T^2 >}{T^2} \qquad p_T u_T << T$$



Scaling Tests

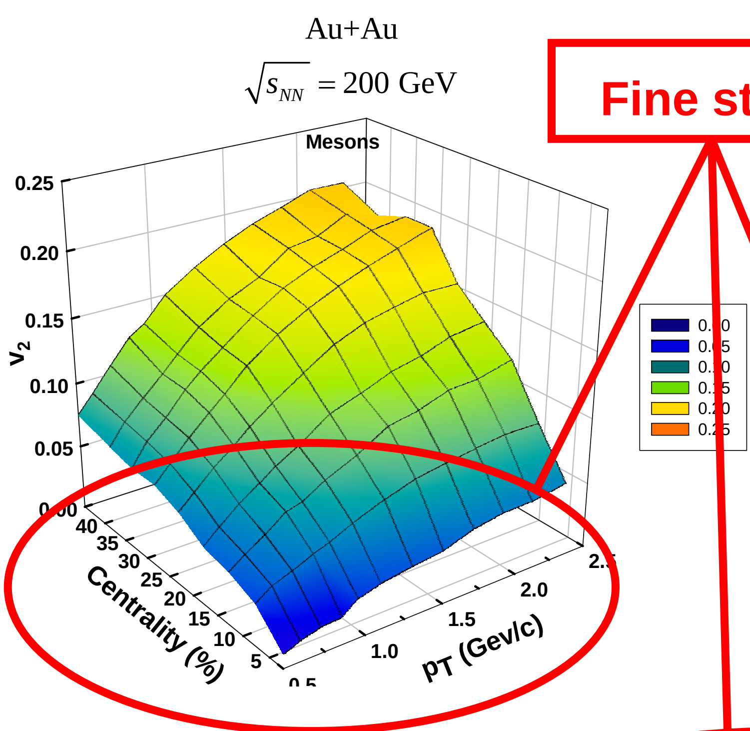


$$A_2 = \frac{v_2}{\varepsilon}$$

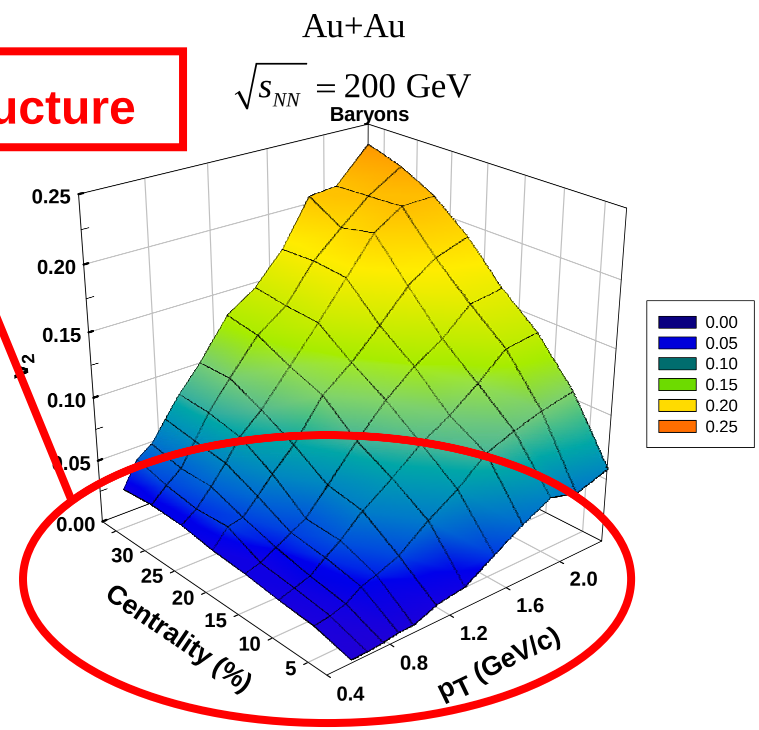
$$\varepsilon = \frac{\langle y^2 \rangle - \langle x^2 \rangle}{\langle y^2 \rangle + \langle x^2 \rangle}$$

→ v2 scales with initial geometry

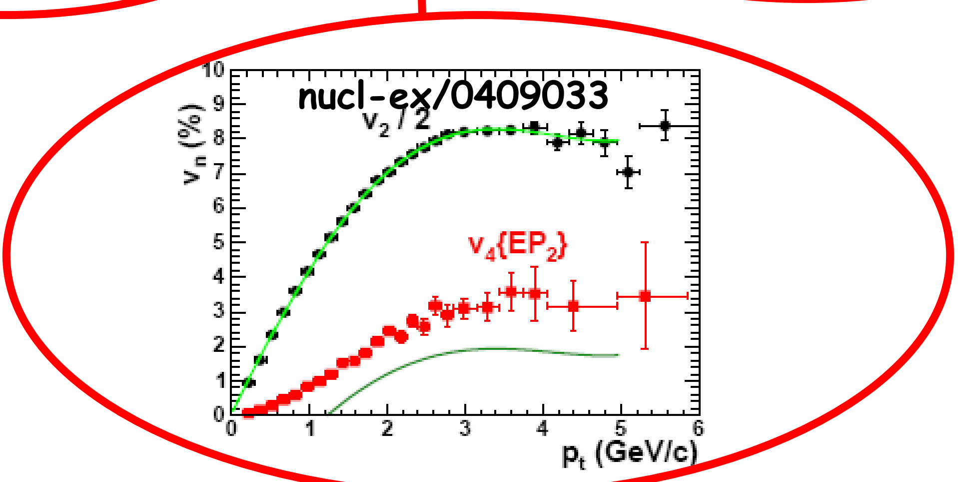
A novel type of scaling: Fine Structure Scaling



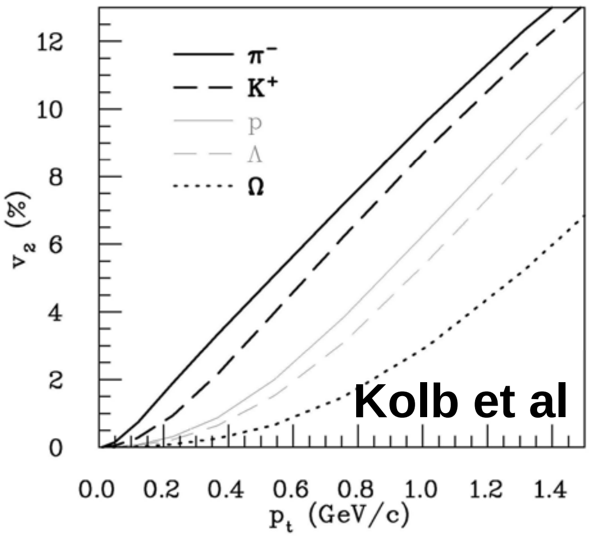
Fine structure



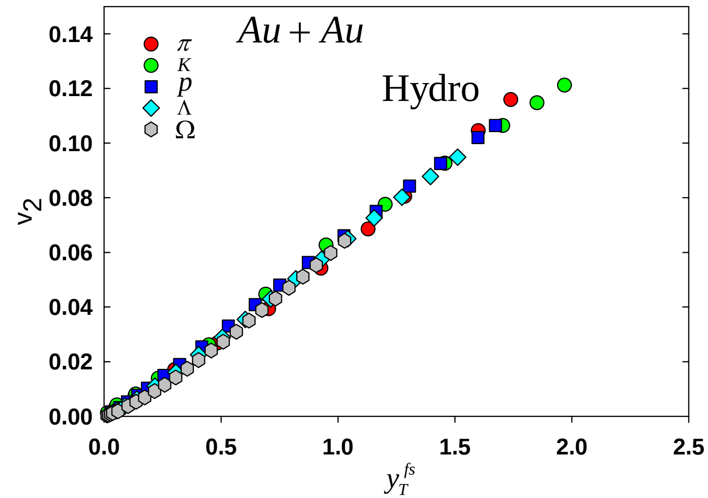
Look for scaling in the whole wealth of available v2 data!

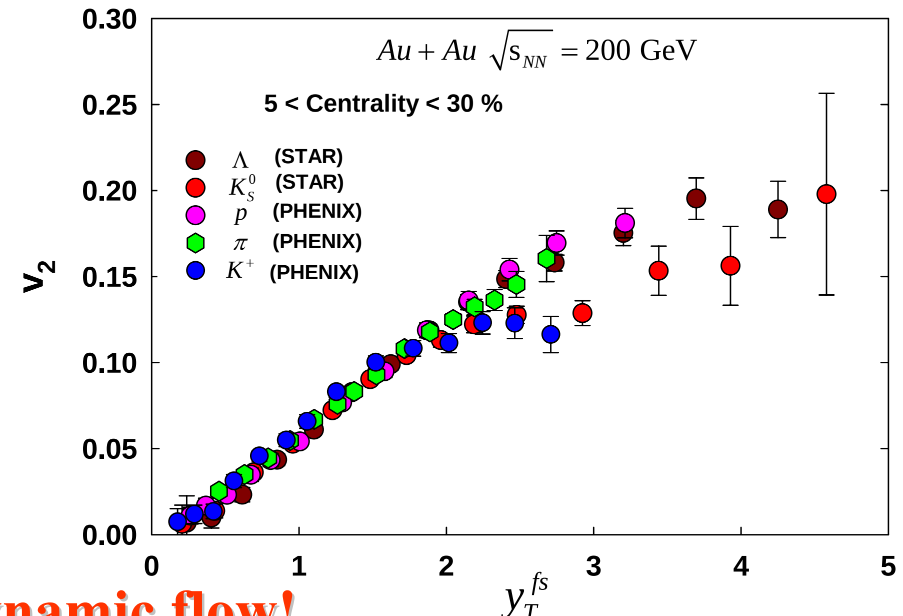


Fine structure scaling at RHIC?



Scaling hydro





$$p_T \rightarrow y_T = \sinh^{-1}(p_T / m)$$

Buda Lund Hydro Model:

$$v_2 \sim \frac{k_1}{T_0} \times y_T^2 m \left(1 + \frac{k_2}{k_1}\frac{T_0}{m} + \frac{k_3}{k_1}\left(\frac{T_0}{m}\right)^2 + .. \right)$$

$$y_T^{fs} \equiv k_m \times y_T^2 m$$

Compelling evidence for hydrodynamic flow!

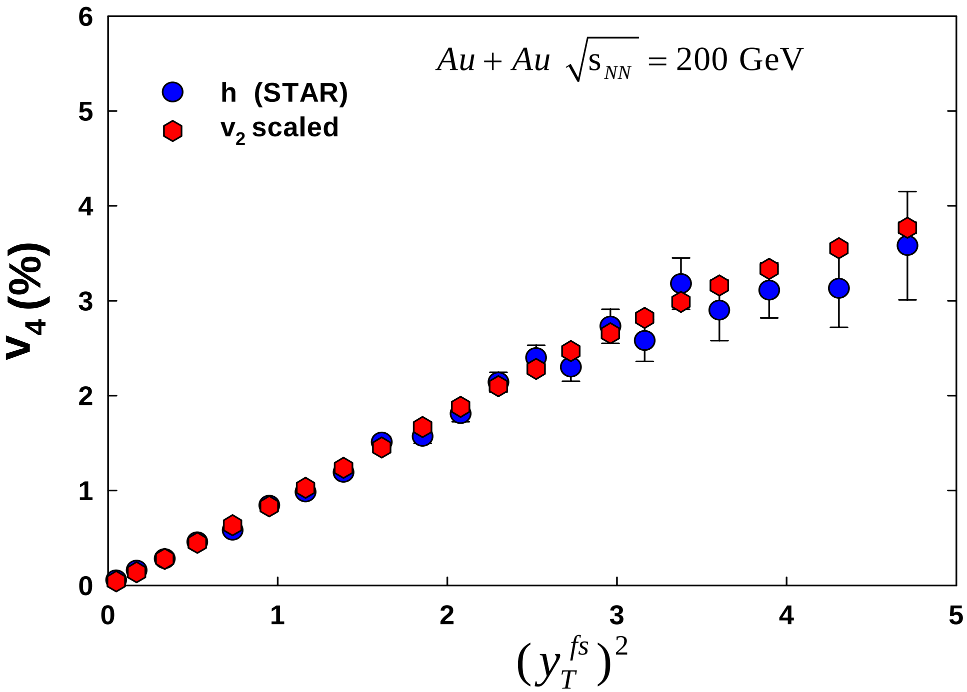
Extended Fine Structure scaling: higher harmonics

$$v_{2n} = \frac{I_n(w)}{I_0(w)}, n = 1,2,...$$

$$v_2 \rightarrow v_4$$

$$v_{2,4} \rightarrow v_6$$

$$v_4 = k_3 y_T^4 \frac{m^2}{T_0^2}\left(1 + \frac{k_4}{k_3}\frac{T_0}{m} + ...\right)$$



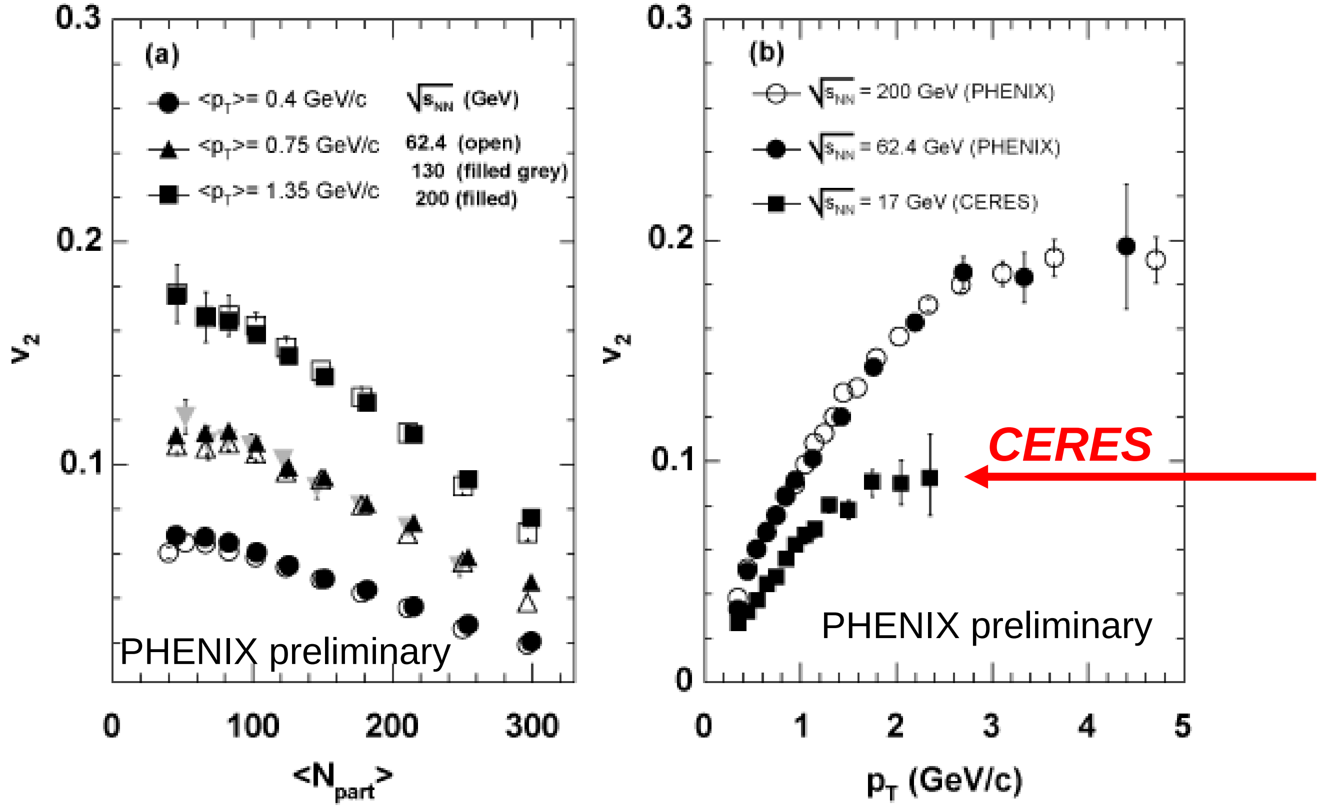
STAR data:

nucl-ex/0409033

Universal scaling prediction!

How unique is this matter?

$\sqrt{s_{NN}} = 17.2, 62.4,\ 130\ \&\ 200\ \text{GeV}$

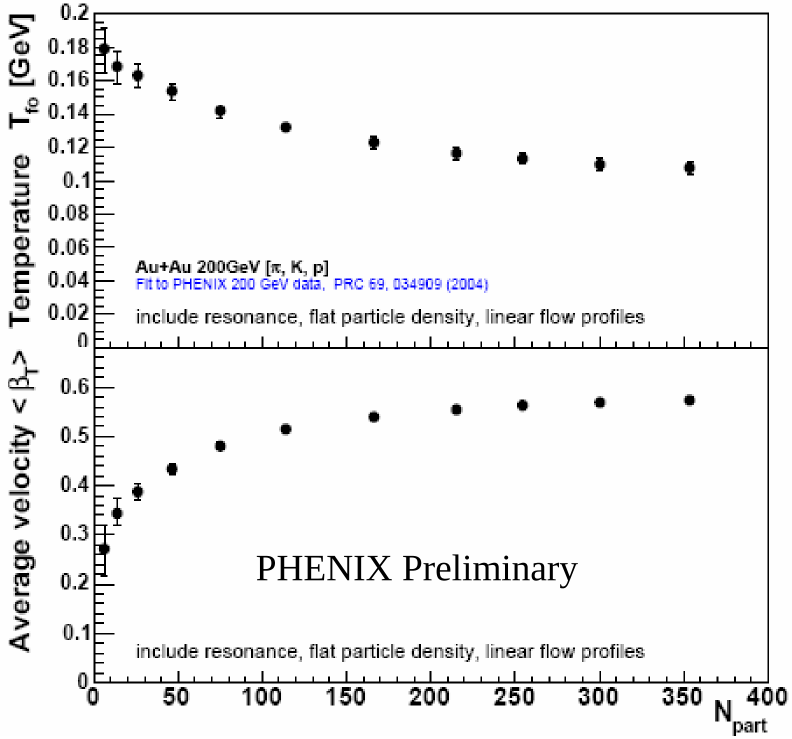


Results are strikingly similar for $\sqrt{s_{NN}} = 62.4,\ 130\ \&\ 200\ \text{GeV}$

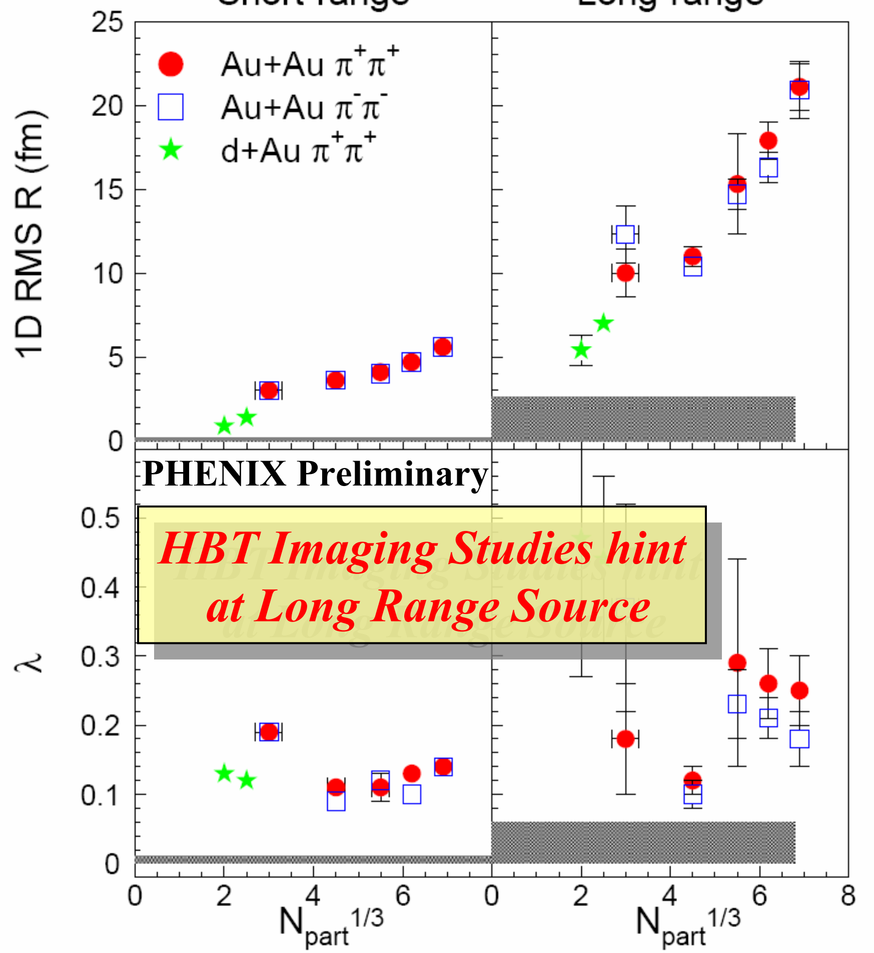
V_2 decreases by ~ 50% from RHIC to SPS

Significantly larger pressure (gradients) at RHIC than at SPS

The fireball rapidly expands



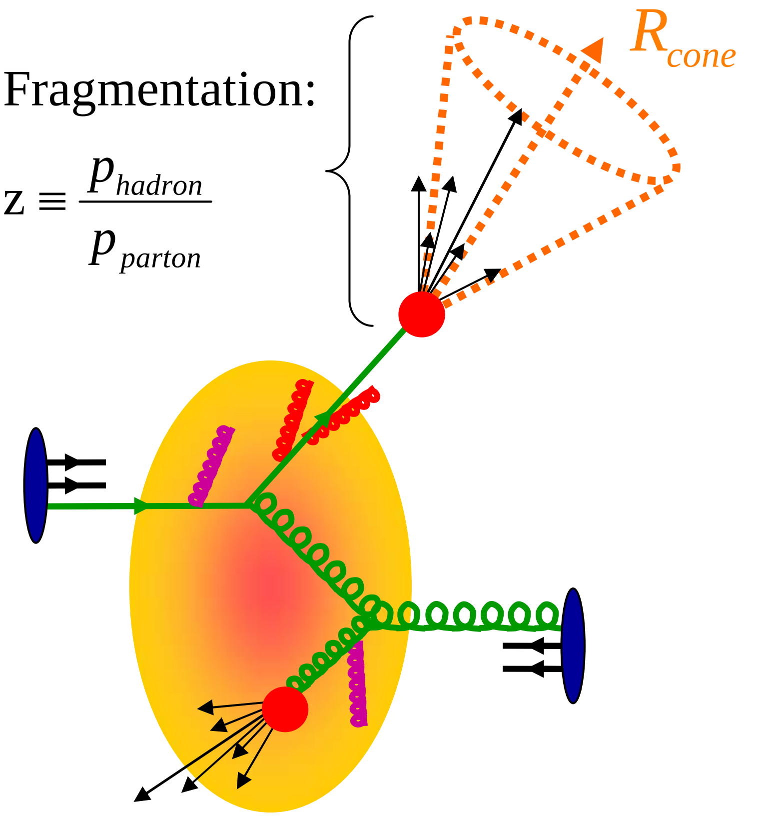
Strong Radial Flow



HBT Imaging Studies hint at Long Range Source

Evidence for strongly interacting matter is compelling!

Diagnostic Probe for the strongly interacting medium: Jets

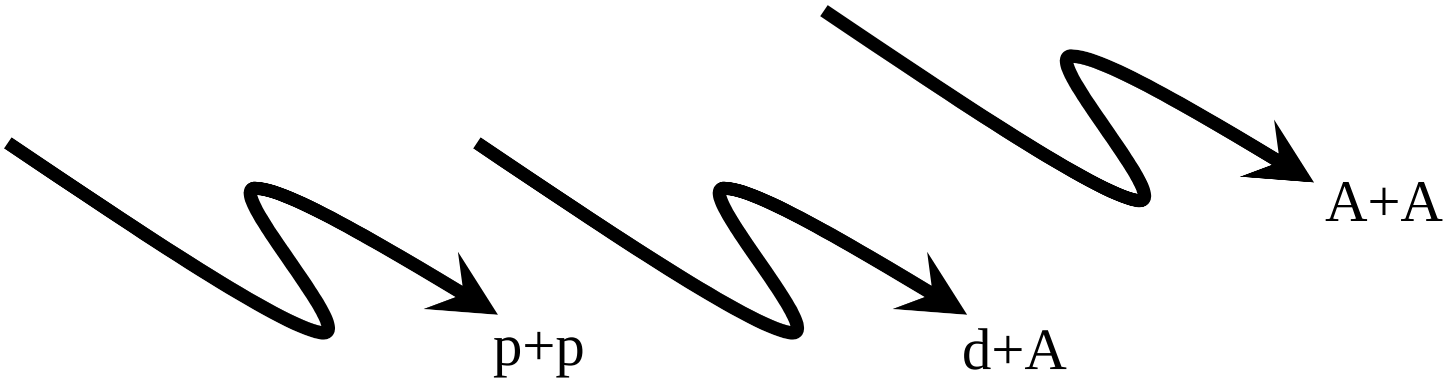


Jets are Remarkable Probes for this High-density Matter

- ***Auto-Generated on the right time-scale***
- ***Calibrated***
- ***Calculable (pQCD)***
- ***Accessible statistically via correlations in Au+Au***

Jet Correlations

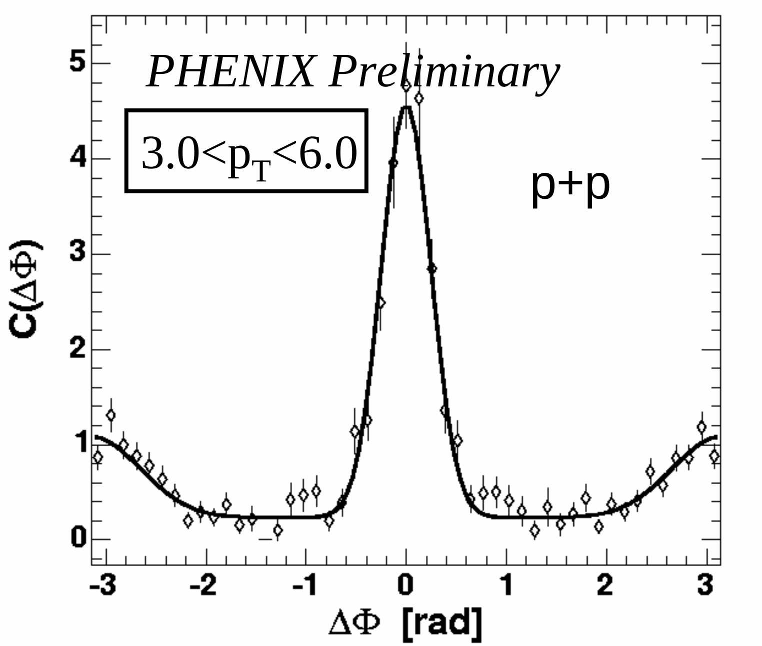
Operational Strategy

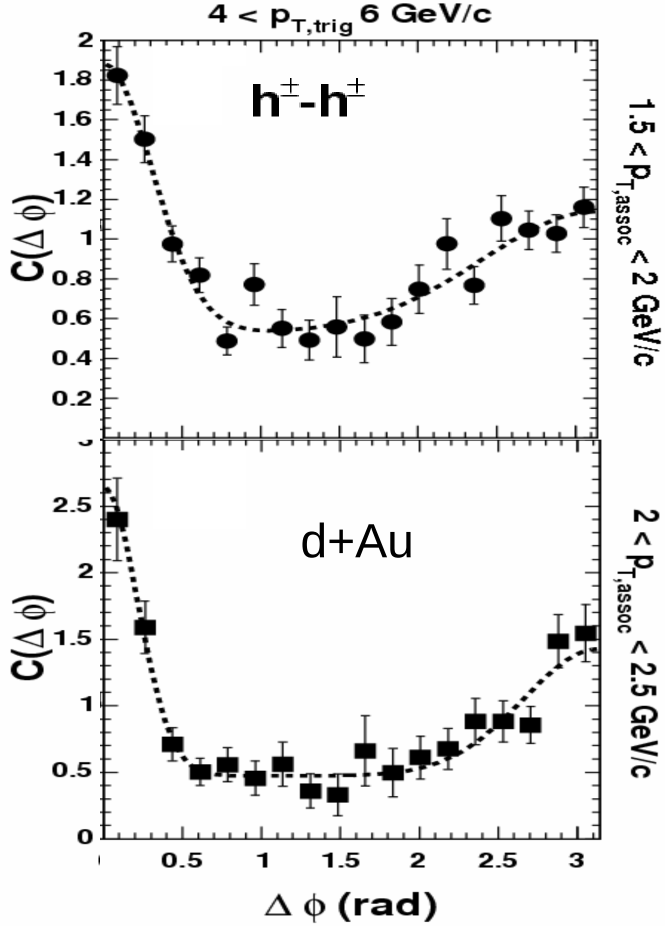


Observable →

$$\langle k_\perp^2 \rangle_{AA} = \langle k_\perp^2 \rangle_{vac} + \langle k_\perp^2 \rangle_{IS\ nucl} + \langle k_\perp^2 \rangle_{FS\ nucl}$$

Calibrated Signal

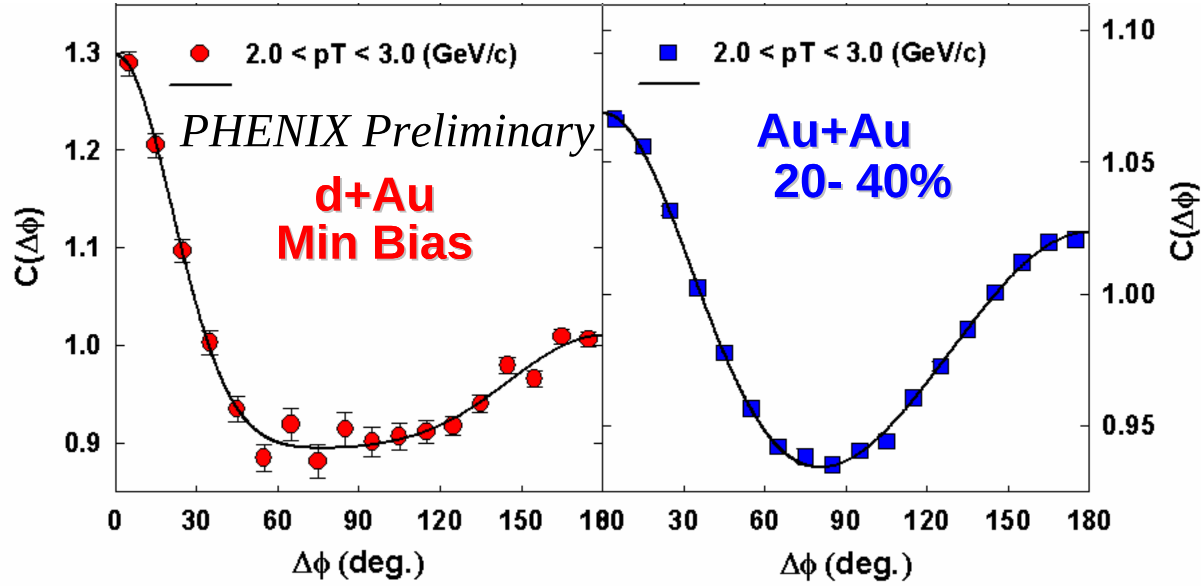




Distinct Di-jet peaks observed for p + p and d + Au

Extracted Di-jet properties similar for both systems

Decompostion Motivation



Au+Au: Asymmetries and Anisotropies -> Need for Decomposition

ZYAM Decompostion of Correlation Function

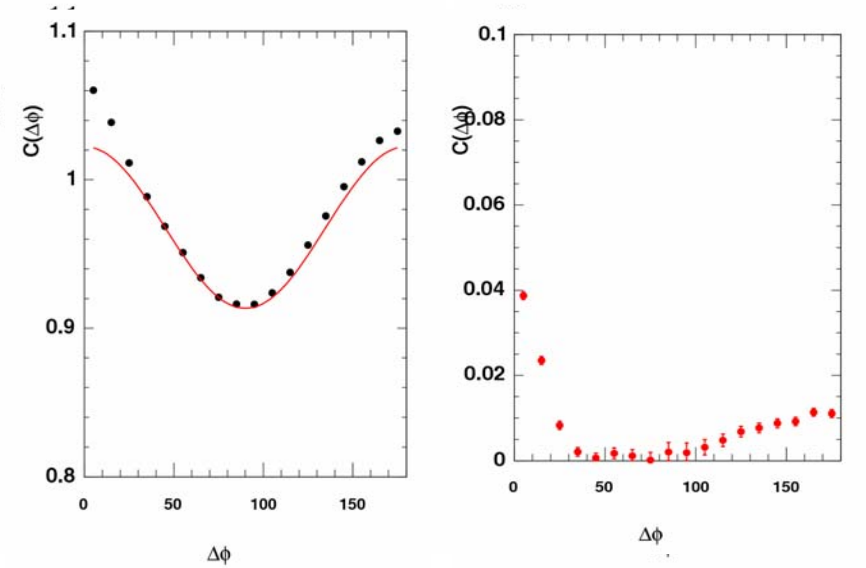
nucl-ex/0501025

Two source model : Flow (H) & Jet (J)

$$\overbrace{C(\Delta\phi)}^{\text{Correlation Function}} = a_0 \left[\overbrace{H(\Delta\phi)}^{\text{Harmonic}} + \overbrace{J(\Delta\phi)}^{\text{Jet Function}} \right]$$

$$\overbrace{J(\Delta\phi)}^{\text{Jet Function}} = \frac{\left[C(\Delta\phi) - a_0 H(\Delta\phi)\right]}{a_0}$$

H(v2)
Obtain v_2 externally
(from RP measurement with Large η gap)



a_0 is obtained without putting any constraint on the Jet shape by requiring

$$J(\Delta\phi_{\min}) = 0$$

i.e. Zero Yield At Minimum
(ZYAM)

Extracting Yields from Correlation Functions

Two Source Model

$$\overbrace{C(\Delta\phi)}^{\text{Correlation Function}} = a_0\left[\overbrace{H(\Delta\phi)}^{\text{Harmonic}} + \overbrace{J(\Delta\phi)}^{\text{Jet Function}}\right]$$

$$H(\Delta\phi) = 1 + 2p_2\cos(2\Delta\phi)$$

$$p_2 = v_2^A \times v_2^B$$

Jet-Pair Fraction:

$$JPF = \sum a_0 J(\Delta\phi) / \sum C(\Delta\phi)$$

Efficiency corrected Conditional yield (CY):

$$CY = JPF \times \frac{n_t^{AB}}{n_t^A \times n_t^B} \times n_t^B$$

Eff. Corrected pair rate (n_t^{AB})

Eff. Corrected Singles yields ($n_t^A \times n_t^B$)

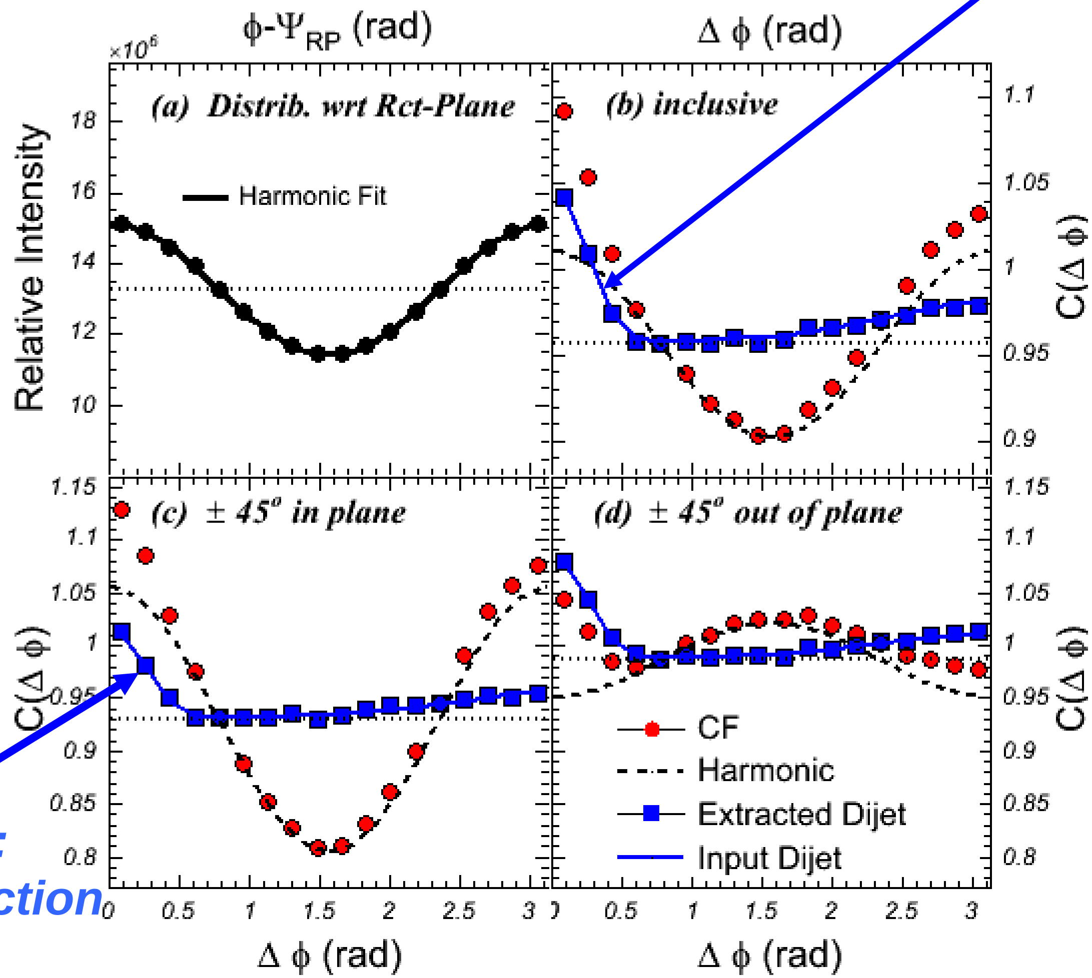
Efficiency corrected Conditional yield (CY):

$$CY = JPF \times \frac{n^{AB}}{n^A \times n^B} \times n_t^B$$

Recorded values ($\frac{n^{AB}}{n^A \times n^B}$)

Simulation Test of Ansatz

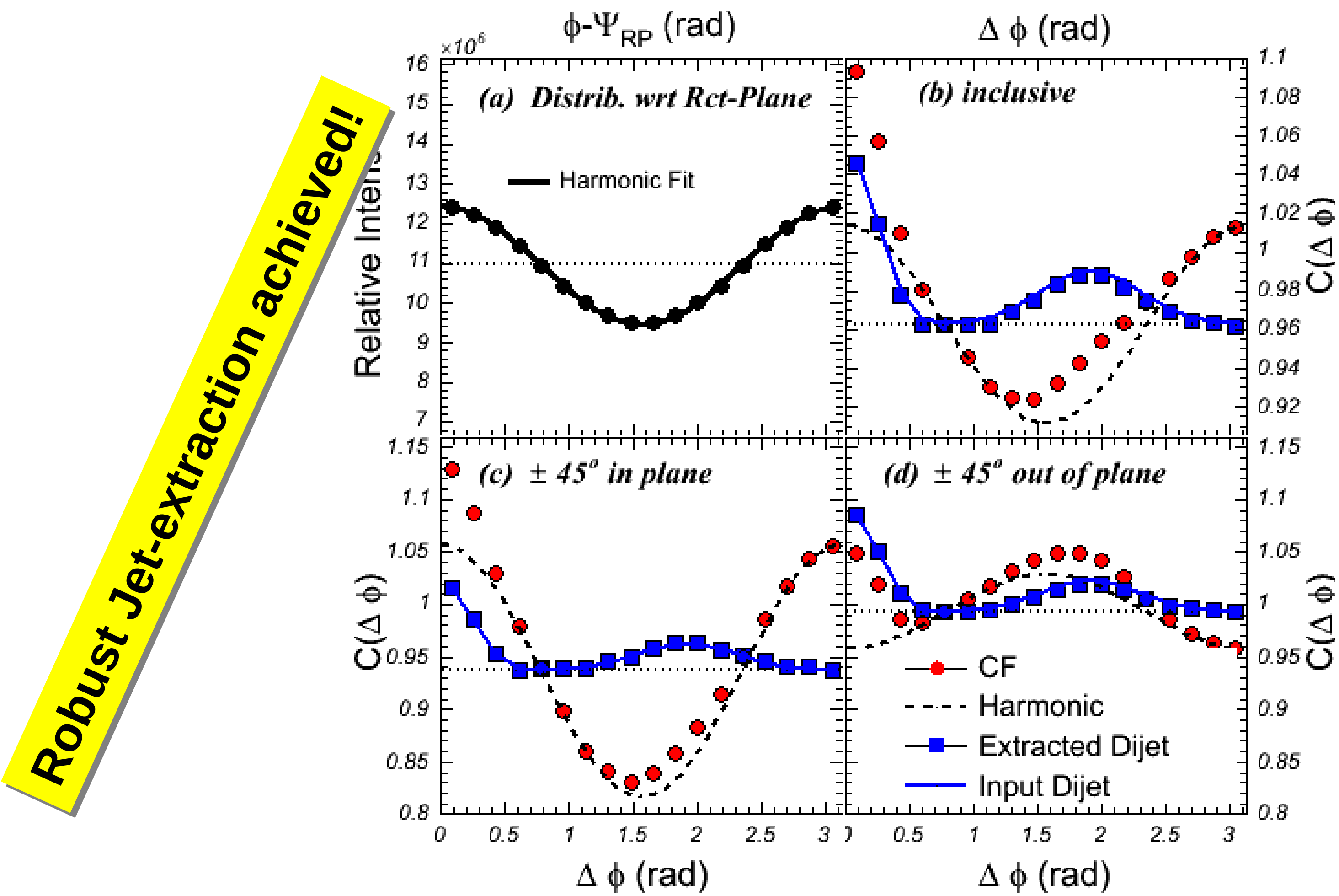
Blue line: input jet-function obtained from Tagging jet-particles in simulation



Blue squares: Extracted jet-function

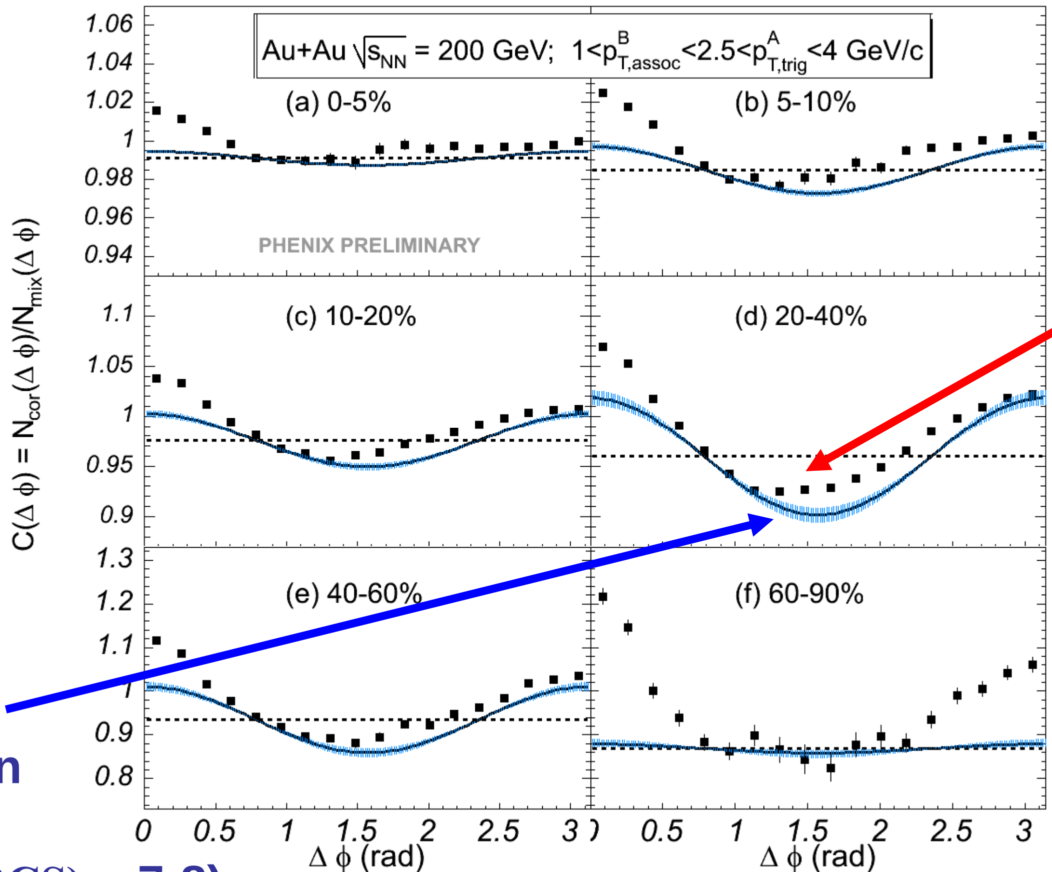
Input jet extremely well recovered!

Simulation Test of Ansatz: Unusual Jet shapes



Input jet faithfully recovered even with unusual jet-shapes!

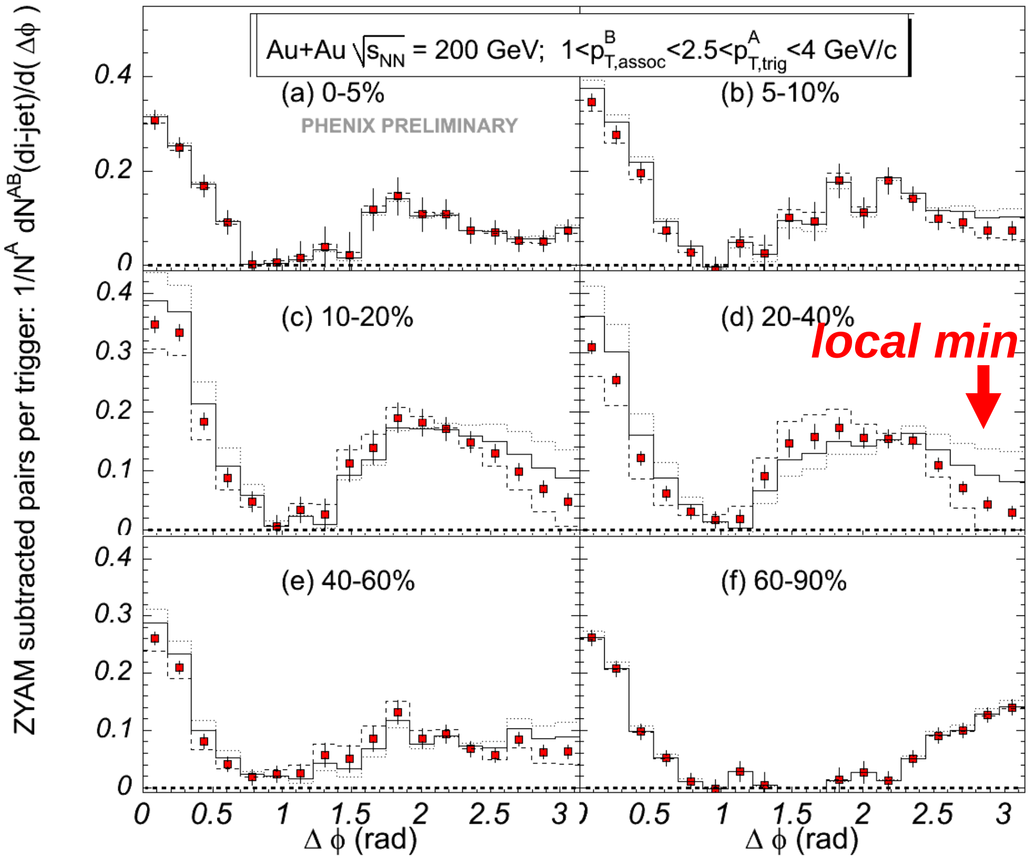
Application of ZYAM Method to PHENIX Data



Minimum of CFctn < 90 deg Modified away-side jet

v_2 from BBC Reaction Plane ($\Delta\eta$(BBCN-BBCS) = 7-8)

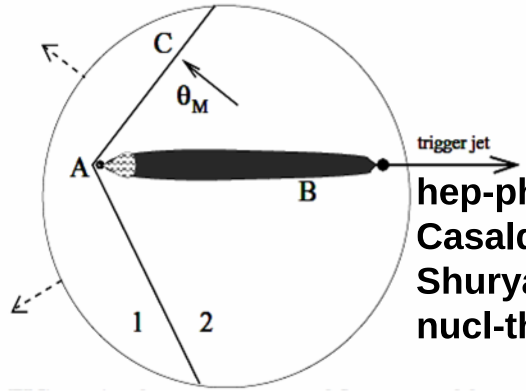
Subtracted jet-pair distributions



(Folded into 0-π)

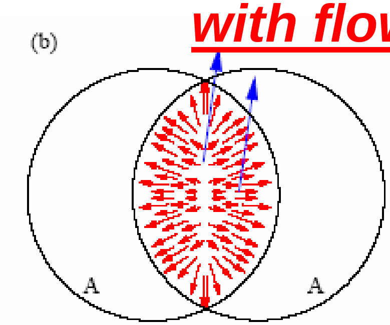
How crazy are those shapes?

Wake effect or "sonic boom"



hep-ph/0411315 Casalderrey-Solana, Shuryak,Teaney
nucl-th/0406018 Stoecker

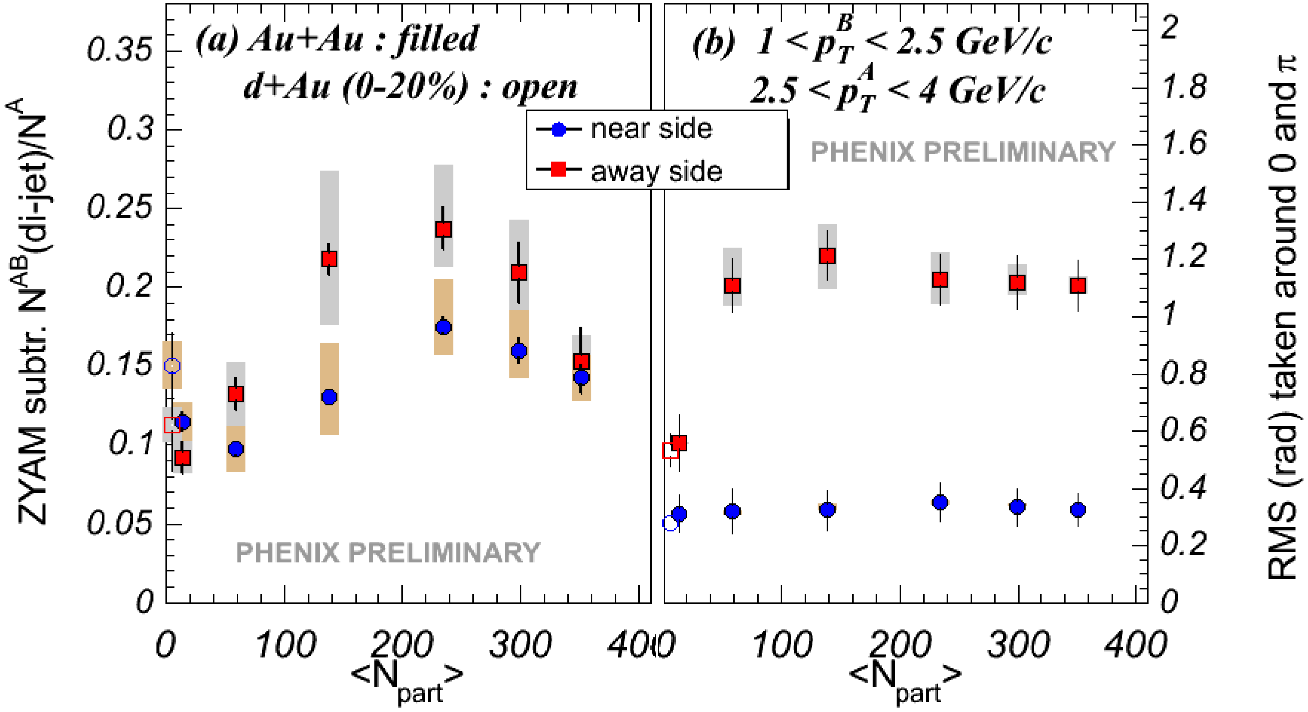
Correlations of Jets with flowing medium



hep-ph/0411341 Armesto,Salgado,Wiedemann

Significant Broadening and Strong Modification of away-side Jet observed!

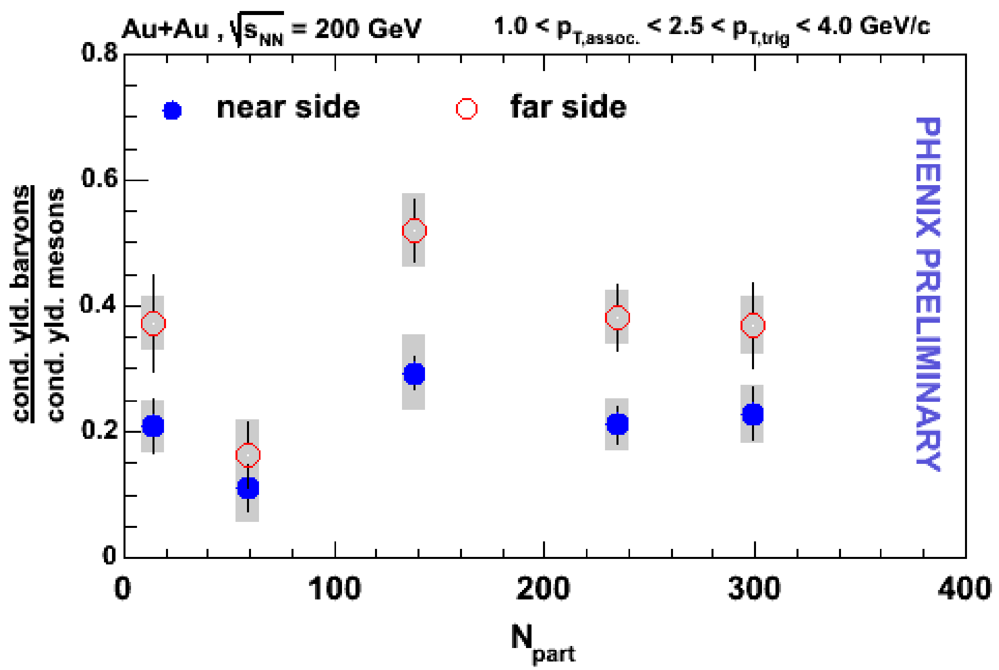
Extracted Jet Yields and Widths



Compelling Evidence for Modification of Jet-Properties

Flavor dependence of jet-yields

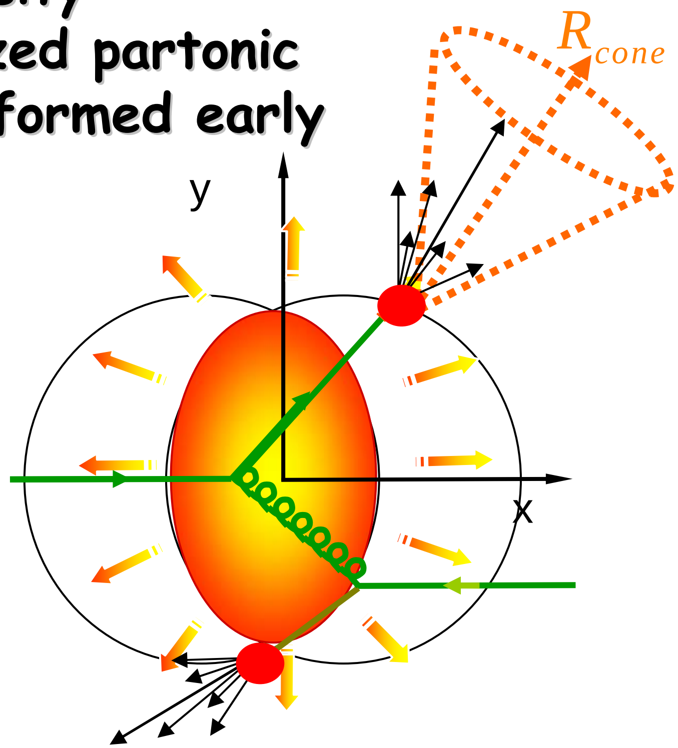
Centrality dependent ratio of jet-yields for associated mesons and baryons



Observed baryon to meson ratio is higher for away-side jets
Flavor dependent in-medium modification?

Possible Emerging Picture

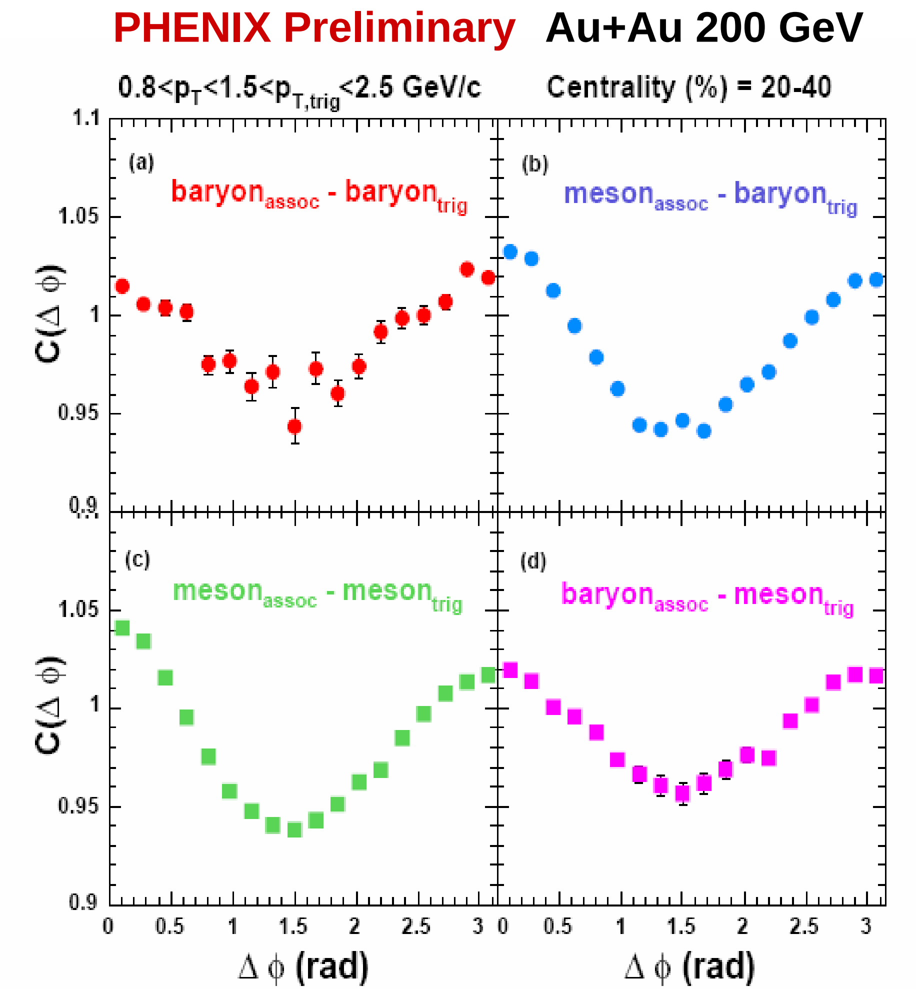
High Density
Thermalized partonic
material formed early



Hard Scattered Partons
Traverse rapidly expanding
partonic material
→ Jet-modification (early) & v2

Correlation measurements suggest compelling evidence for strongly interacting high energy density matter not heretofore seen!

The Next Step: Flavor Permutation

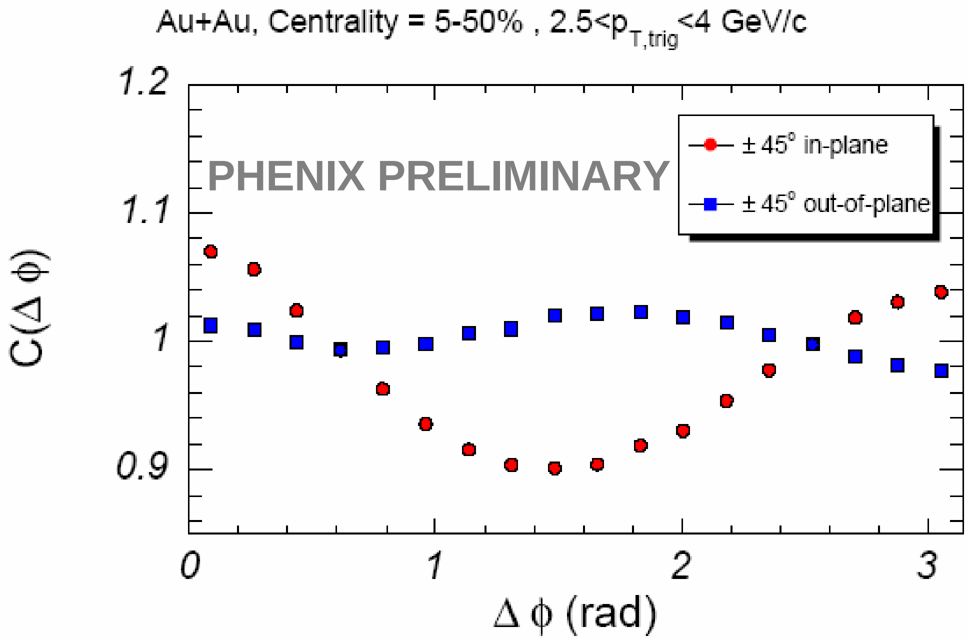


Flavor Permutations matter!

Extensive Range of studies currently being finalized

(… Stay tuned for QM2005)

Towards determining the mechanistic origin of modification



Reaction Plane Dependent Decomposition of flavor permutations might yield the answer!

PHENIX

12 Countries; 58 Institutions; 480 Participants*

Country	Institution
Brazil	University of São Paulo, São Paulo
China	Academia Sinica, Taipei, Taiwan
	China Institute of Atomic Energy, Beijing
	Peking University, Beijing
France	LPC, University de Clermont-Ferrand, Clermont-Ferrand
	Dapnia, CEA Saclay, Gif-sur-Yvette
	IPN-Orsay, Universite Paris Sud, CNRS-IN2P3, Orsay
	LLR, Ecòle Polytechnique, CNRS-IN2P3, Palaiseau
	SUBATECH, Ecòle des Mines at Nantes, Nantes
Germany	University of Münster, Münster
Hungary	Central Research Institute for Physics (KFKI), Budapest
	Debrecen University, Debrecen
	Eötvös Loránd University (ELTE), Budapest
India	Banaras Hindu University, Banaras
	Bhabha Atomic Research Centre, Bombay
Israel	Weizmann Institute, Rehovot
Japan	Center for Nuclear Study, University of Tokyo, Tokyo
	Hiroshima University, Higashi-Hiroshima
	KEK, Institute for High Energy Physics, Tsukuba
	Kyoto University, Kyoto
	Nagasaki Institute of Applied Science, Nagasaki
	RIKEN, Institute for Physical and Chemical Research, Wako
	RIKEN-BNL Research Center, Upton, NY
	Rikkyo University, Tokyo, Japan
	Tokyo Institute of Technology, Tokyo
	University of Tsukuba, Tsukuba
	Waseda University, Tokyo
S. Korea	Cyclotron Application Laboratory, KAERI, Seoul
	Kangnung National University, Kangnung
	Korea University, Seoul
	Myong Ji University, Yongin City
	System Electronics Laboratory, Seoul Nat. University, Seoul
	Yonsei University, Seoul
Russia	Institute of High Energy Physics, Protovino
	Joint Institute for Nuclear Research, Dubna
	Kurchatov Institute, Moscow
	PNPI, St. Petersburg Nuclear Physics Institute, St. Petersburg
	St. Petersburg State Technical University, St. Petersburg
Sweden	Lund University, Lund
USA	Abilene Christian University, Abilene, TX
	Brookhaven National Laboratory, Upton, NY
	University of California - Riverside, Riverside, CA
	University of Colorado, Boulder, CO
	Columbia University, Nevis Laboratories, Irvington, NY
	Florida State University, Tallahassee, FL
	Florida Technical University, Melbourne, FL
	Georgia State University, Atlanta, GA
	University of Illinois Urbana Champaign, Urbana-Champaign, IL
	Iowa State University and Ames Laboratory, Ames, IA
	Los Alamos National Laboratory, Los Alamos, NM
	Lawrence Livermore National Laboratory, Livermore, CA
	University of New Mexico, Albuquerque, NM
	New Mexico State University, Las Cruces, NM
	Dept. of Chemistry, Stony Brook Univ., Stony Brook, NY
	Dept. Phys. and Astronomy, Stony Brook Univ., Stony Brook, NY
	Oak Ridge National Laboratory, Oak Ridge, TN
	University of Tennessee, Knoxville, TN
	Vanderbilt University, Nashville, TN

*as of January 2004