What have we learned from Anisotropic Flow at RHIC ?

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for the PHENIX Collaboration

2006 RHIC & AGS Annual User's meeting

June 5 – 9, 2006 at Brookhaven National Laboratory

Workshop 8 : How perfect is this matter ?

“Perfect liquid” at RHIC

PHENIX

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RHIC Scientists Serve Up “Perfect” Liquid

New state of matter more remarkable than predicted -- raising many new ques

April 18, 2005

TAMPA, FL -- The four detector groups conducting research at the Relativistic Heavy I -- a giant atom "smasher" located at the U.S. Department of Energy's Brookhaven Natio say they've created a new state of hot, dense matter out of the quarks and gluons tha particles of atomic nuclei, but it is a state quite different and even more remarkable tha predicted. In peer-reviewed papers summarizing the first three years of RHIC findings, t that instead of behaving like a gas of free quarks and gluons, as was expected, the mat RHIC's heavy ion collisions appears to be more like a *liquid*.

"Once again, the physics research sponsored by the Department of Energy is producing historic results," said Secretary of Energy Samuel Bodman, a trained chemical engineer. "The DOE is the principal federal funder of basic research in the physical sciences, including nuclear and high-energy physics. With today's announcement we see that investment paying off."

"The truly stunning finding at RHIC that the new state of matter created in the collisions of gold ions is more like a liquid than a gas gives us a profound insight into the earliest moments of the universe," said Dr. Raymond L. Orbach, Director of

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宇宙の始まりはしずく？　「クオークは液体」と発表

2005年04月18日23時34分

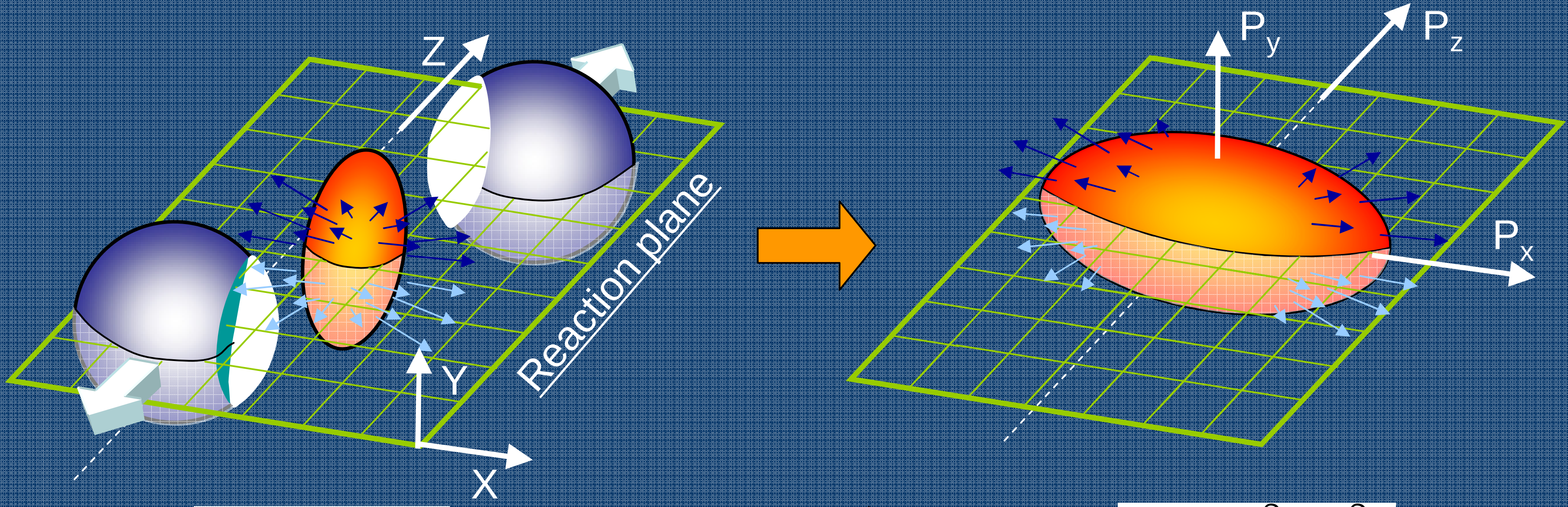
宇宙誕生の大爆発「ビッグバン」直後に相当する超高温・高密度の状態を再現する実験をしてきた日米などの国際チームは１８日、物質を形づくる究極の基本粒子クオークは超高温でバラバラになるが、気体のように自由に跳び回るのでなく、しずくのような液体状態にあったと考えられる、と発表した。理論的に予想外の発見で、宇宙や物質のなりたちを説明するシナリオに影響を与える可能性がある。

基本粒子クオークとそれらをくっつける「のり」の役をするグルーオンという素粒子は、超高温の宇宙初期にはバラバラで存在していたが、冷えた今の宇宙では、強い力で陽子などの中に閉じこめられ、１個ずつ引き離すのは難しい。

チームは００年から米ブルックヘブン国立研究所で、ほぼ光速で走る金のイオン同士を衝突させ、ビッグバンの数十万分の１秒後にあたる１兆度以上の「クオークとグルーオンのかたまり」を作ってきた。そこから飛び出した粒子の軌跡などを解析したところ、かたまりは、粘り気がないサラサラした液体の性質を示すことが分かった。

- Strong collective flow, nearly perfect liquid

Definitions



$$\epsilon = \left\langle \frac{y^2 - x^2}{y^2 + x^2} \right\rangle$$

$$v_2 = \left\langle \frac{p_x^2 - p_y^2}{p_x^2 + p_y^2} \right\rangle$$

- Anisotropic Flow
  - Azimuthal correlation to reaction plane
  - Elliptic flow (v_2)

$$E\frac{d^3N}{dp^3} = \frac{1}{2\pi}\frac{d^2N}{p_T dp_T dy}\left(1 + \sum_{n=1}^{\infty} 2v_n \cos\left[n(\phi - \Psi)\right]\right)$$

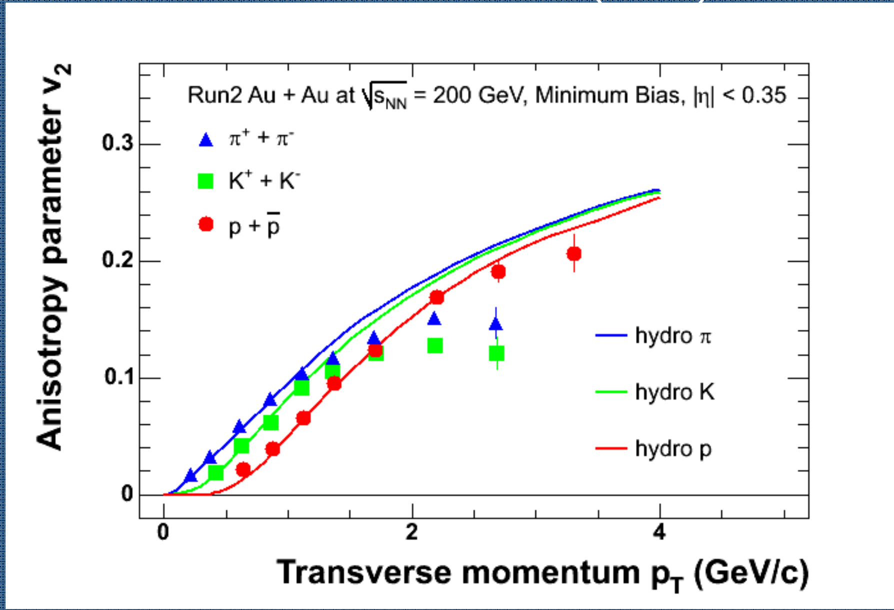
$$v_n = \langle \cos\left(n(\phi - \Psi)\right) \rangle$$

Outline

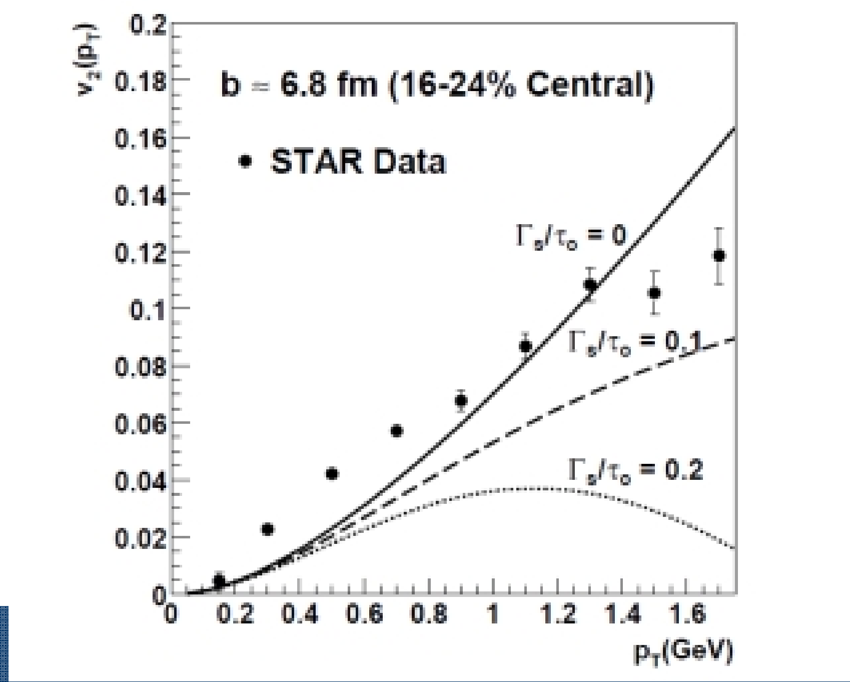
- Elliptic Flow and Hydrodynamics
- PHENIX experiment
  - Particle identification, event plane
- Eccentricity scaling and speed of sound
- Kinetic energy (Hydro) scaling and Partonic collectivity
- Summary

v_2 and hydrodynamics

PHENIX : PRL 91, 182301 (2003)

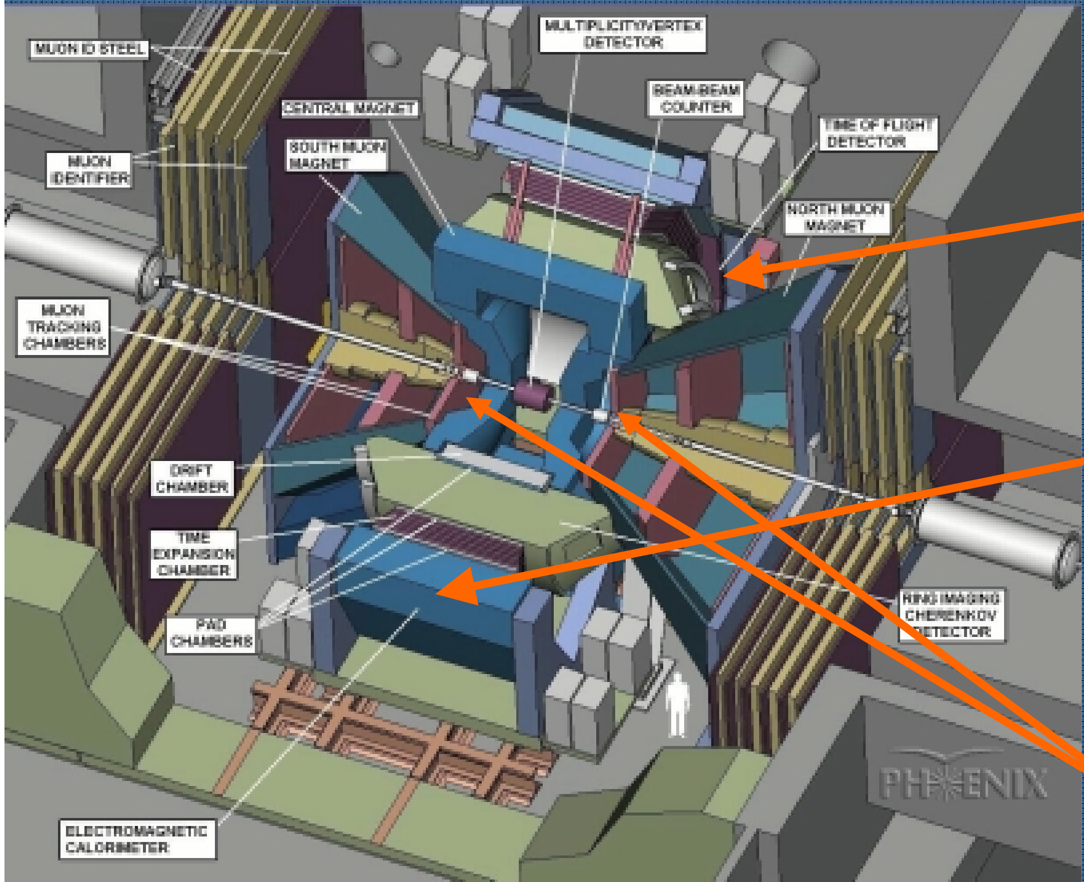


D. Teaney : PRC 68, 034913 (2003)



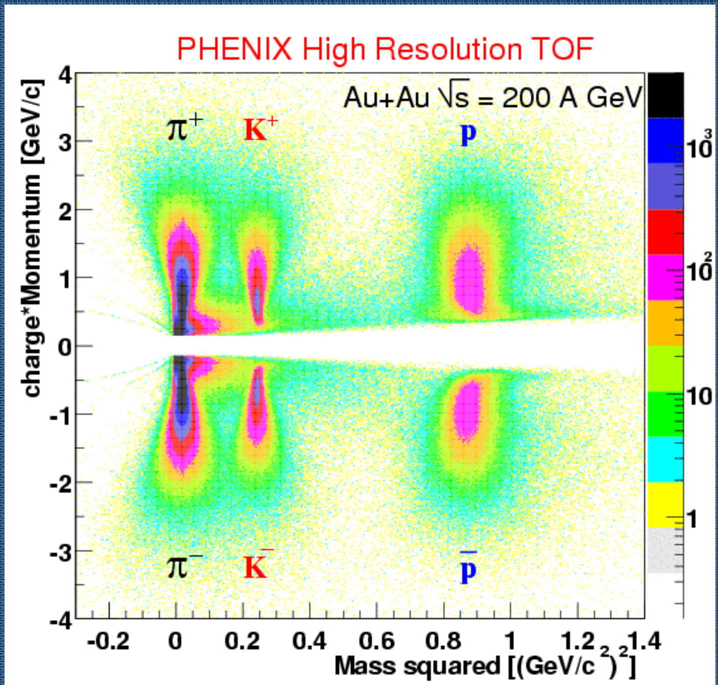
- Large elliptic flow at RHIC
- Elliptic flow is well described by hydrodynamics
  - Magnitude, particle type up to p_T ~ 1.5 GeV/c
  - Indicate early thermalization τ < 1 fm/c, extremely low viscosity < 0.1

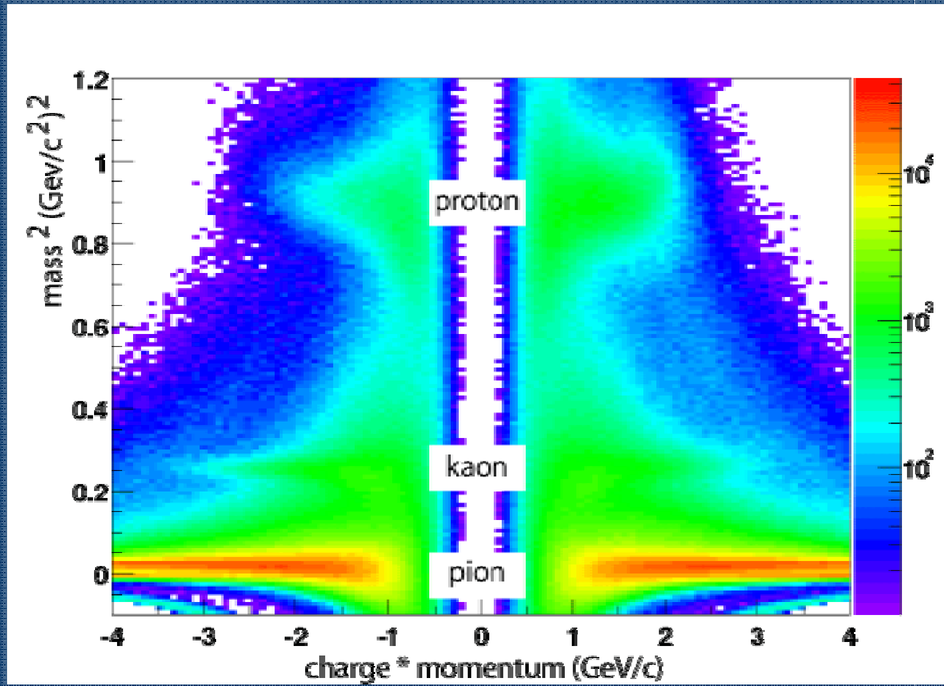
PHENIX experiment



- Hadron identification
  - Time-of-Flight
    - $|\eta| < 0.35$, $|\phi| < \pi/4$
  - EM Calorimeter
    - $|\eta| < 0.35$, $|\phi| < \pi/2$
- Event plane
  - Beam Beam Counter, $3 < |\eta| < 3.9$, full azimuth

Hadron identification

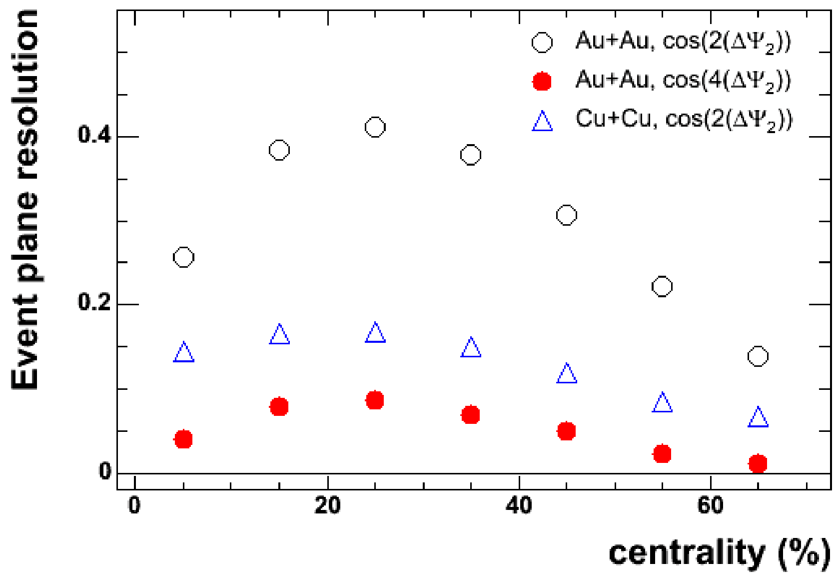


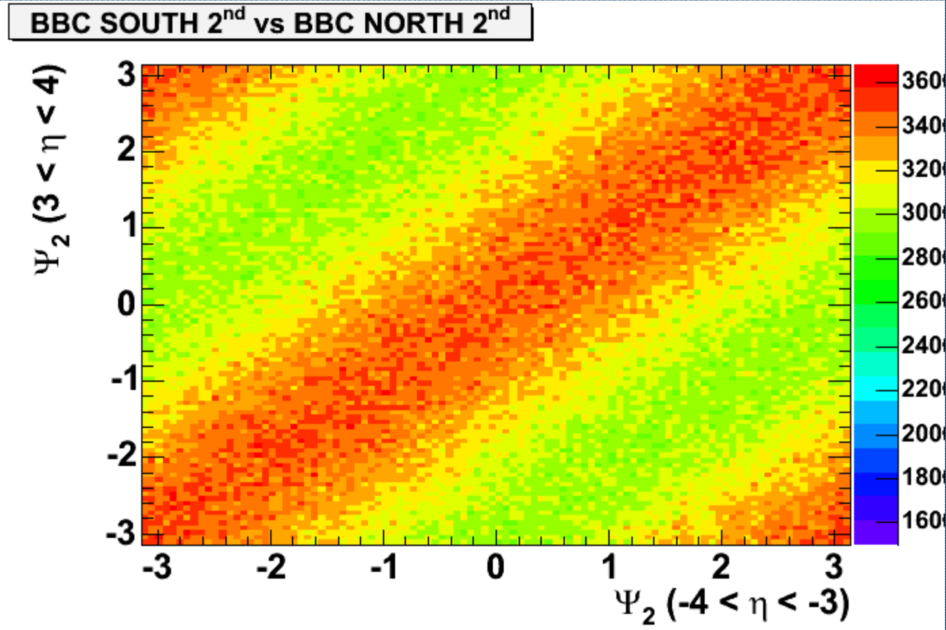


- Time-of-flight
  - $|\phi| < \pi/4$, $|\eta| < 0.35$
  - Timing resolution ~ 120 ps
    - π/K separation ~ 2 GeV/c
    - K/p separation ~ 4 GeV/c
- Good timing resolution

- EM Calorimeter
  - $|\phi| < \pi/2$, $|\eta| < 0.35$
  - Timing resolution ~ 400 ps
    - π/K separation ~ 1 GeV/c
    - K/p separation ~ 2 GeV/c
- Large acceptance

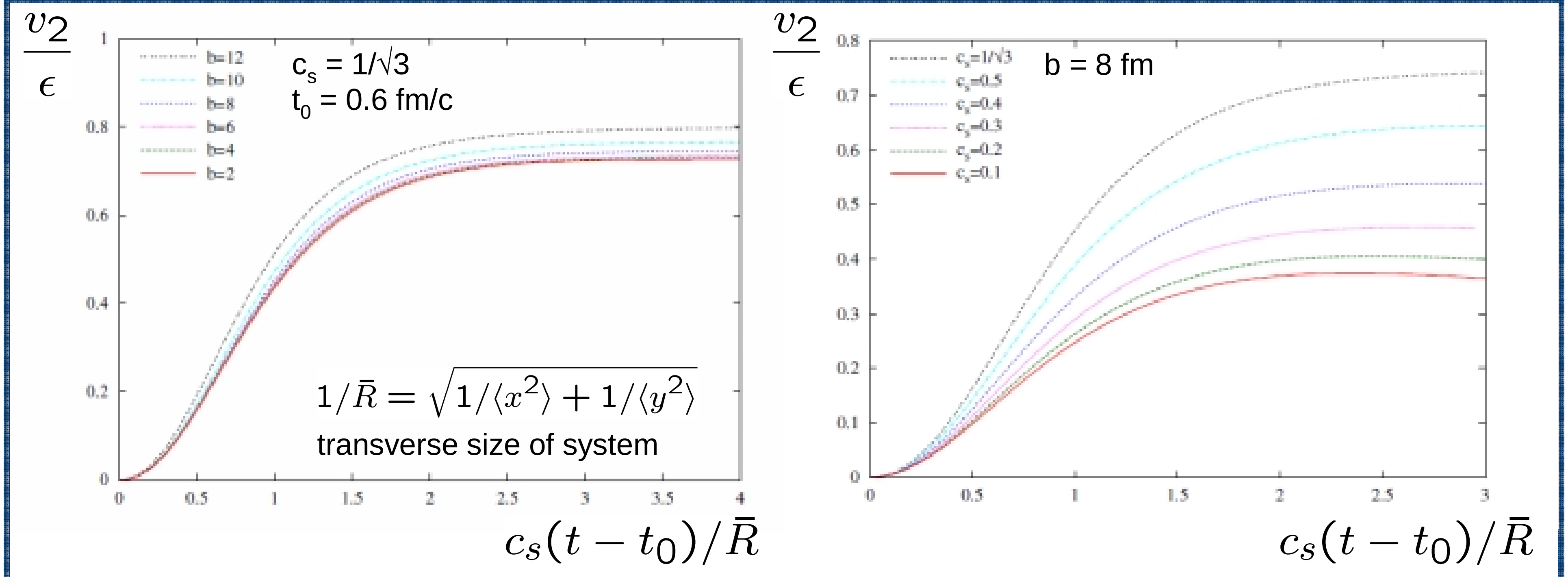
Event plane @ 3<|η|<4





- Large rapidity gap
  - Central arm |η| < 0.35 ⟷ BBC 3 < |η| < 4
  - Smaller non-flow contribution

v_2 from ideal fluid dynamics



R. S. Bhalerao, J.P. Blaizot, N. Borghini, J.-Y. Ollitrault, PLB 627, 49, (2005)

- v_2 scales initial eccentricity (ε)
- v_2/ε is independent on system size R
- v_2 grows with c_s
- Can we test these relations from the data ?

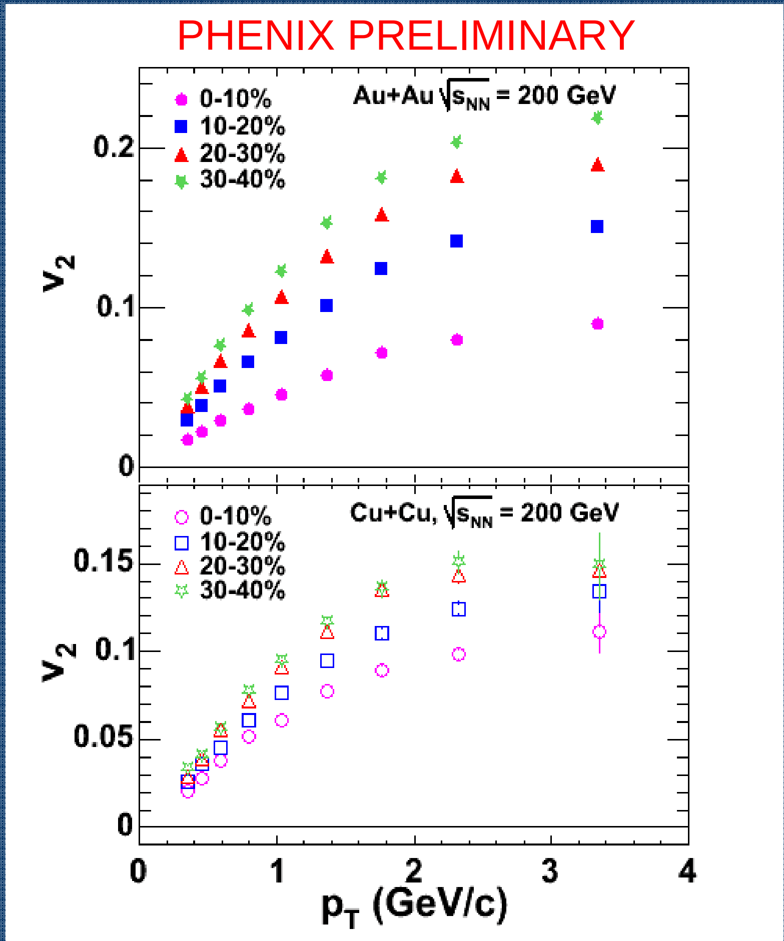
Can we test eccentricity scaling of v_2 ?

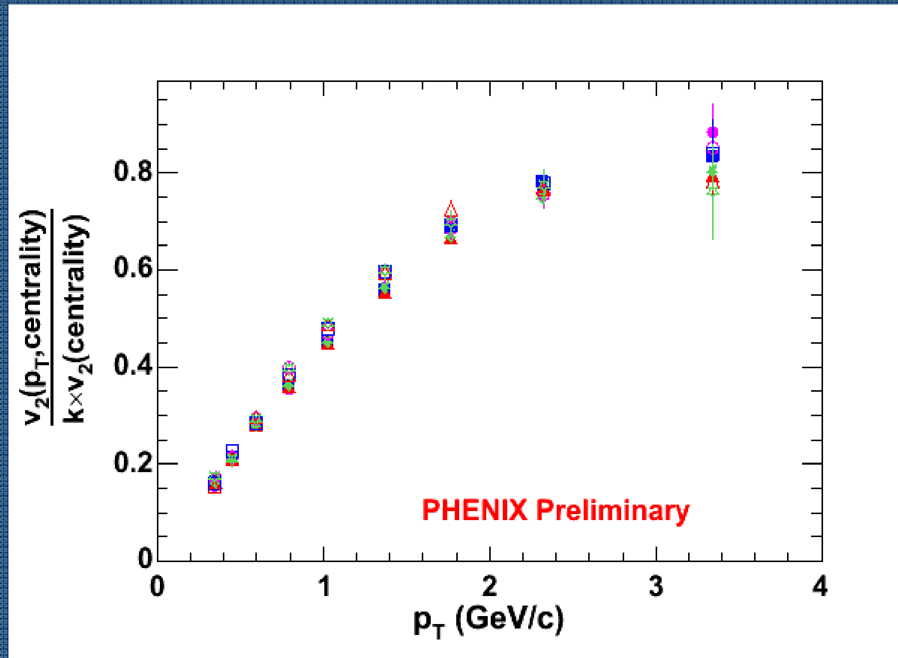
- Does v_2 scale eccentricity ?
  - Centrality dependence of v_2/ε
- Is v_2/ε independent of system size ?
  - Au+Au vs Cu+Cu
- Estimate of speed of sound can be made from the measurement of v_2/ε

Eccentricity and integrated v_2

- Eccentricity is usually estimated by Glauber Model
- Integrated v_2 is proportional to eccentricity
- Advantage of integrated v_2 :
  - Reduce large systematic error from Glauber MC, typically 20 – 30 %
  - Cancel systematic error from event plane determination

Eccentricity scaling

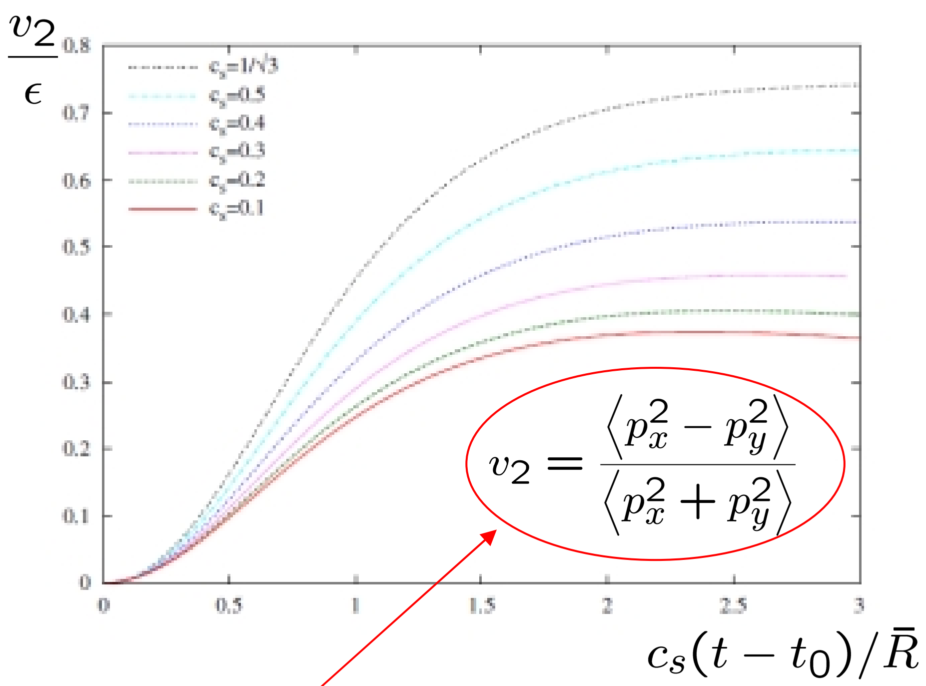


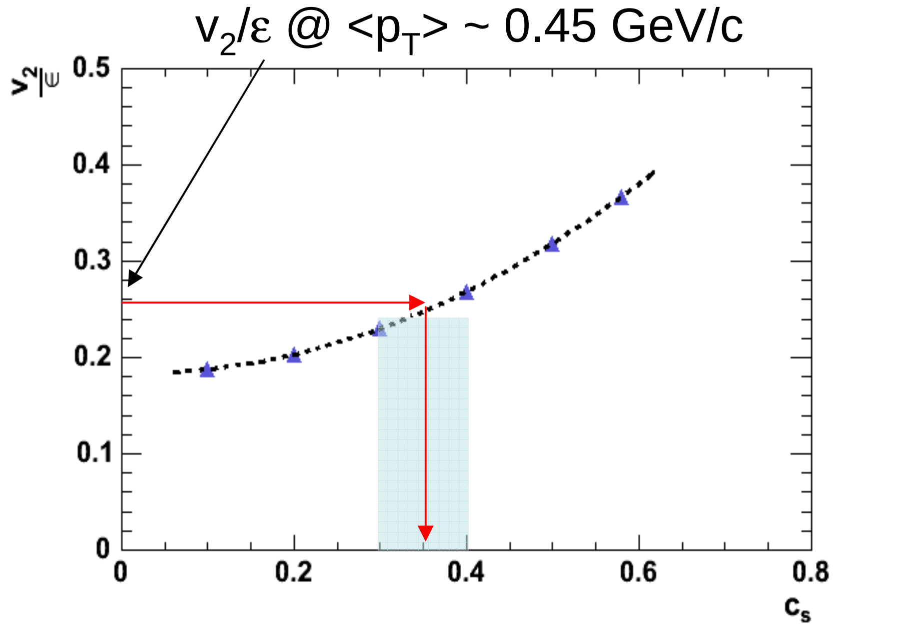


k ~ 3.1 obtained from data

- Scaling holds for a broad range of centrality
  - Centrality 30 -40 %, b ~ 8.7 fm
- Independent of system size

Estimate of c_s

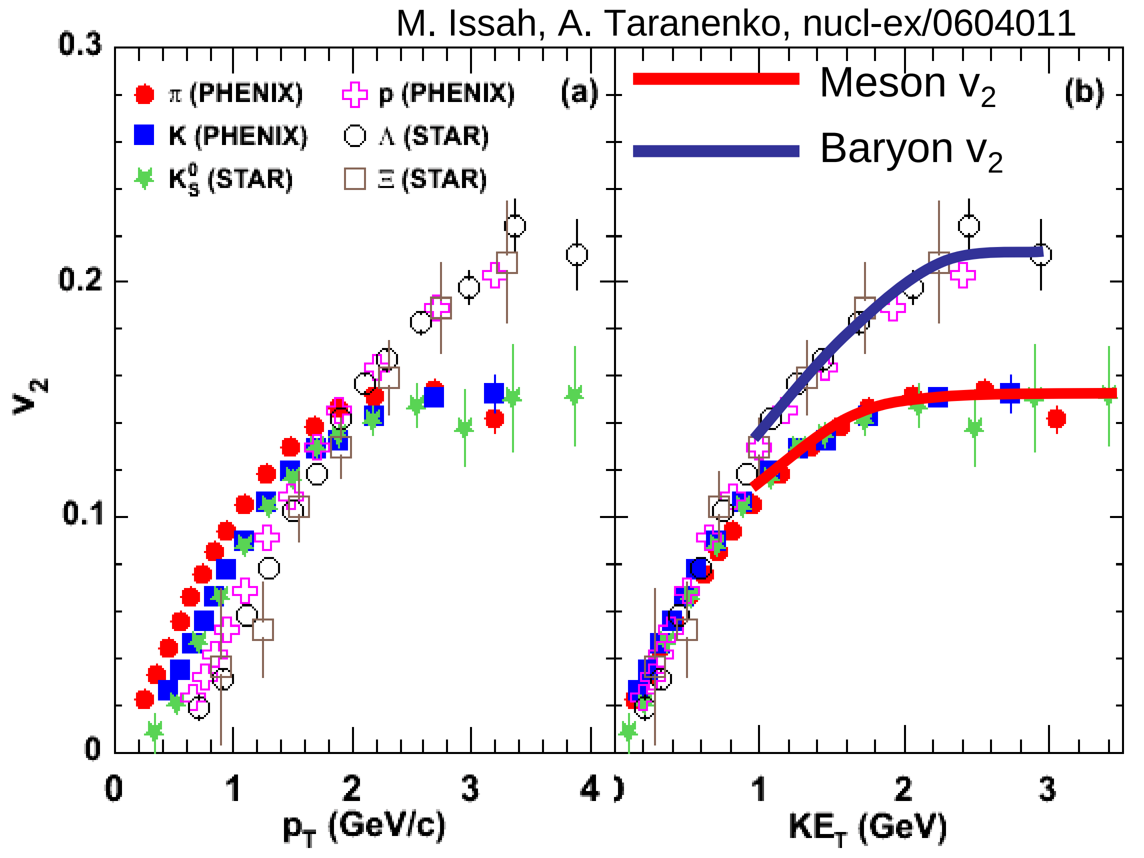




NOTE
v_2 value is typically factor 2 lager than $v_2 = \left\langle \frac{p_x^2 - p_y^2}{p_x^2 + p_y^2} \right\rangle$

- $C_s = 0.35 \pm 0.05$
  - Indicate softer EOS compared to $c_s=1/\sqrt{3}$
  - v_2/ε ~ 0.1 (peripheral) – 0.2 (central) at STAR and PHOBOS
  - Integrated v_2 does not develop so much in the late hadronic stage

Kinetic energy scaling



K^0_S, Λ (STAR) : PRL 92, 052302 (2004)

Ξ (STAR) : PRL 95, 122301 (2005)

π, K, p (PHENIX) : preliminary

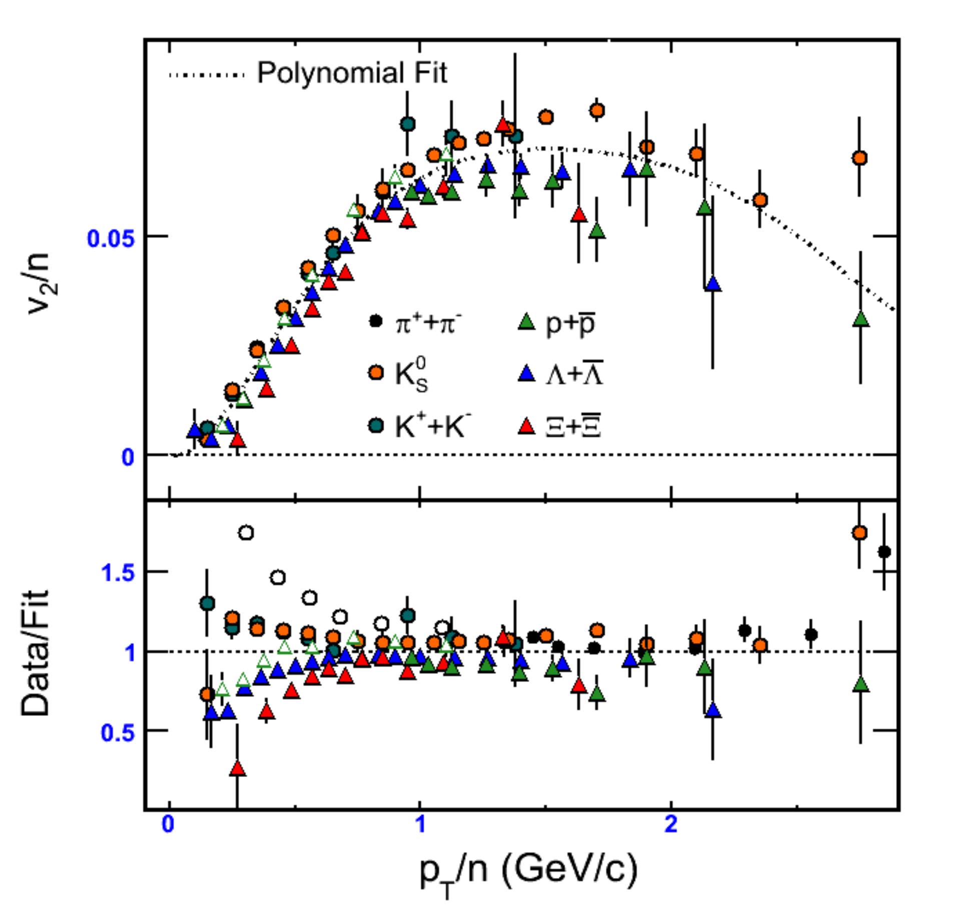
** Kinetic energy of a particle in a relativistic fulid*

$KE_T \sim m_T - m_0$ at $y \sim 0$

Hadron mass

- Kinetic energy scaling works up to KE_T ~ 1 GeV
  - Indicate hydrodynamic behavior
- Possible hint of quark degrees of freedom at higher KE_T

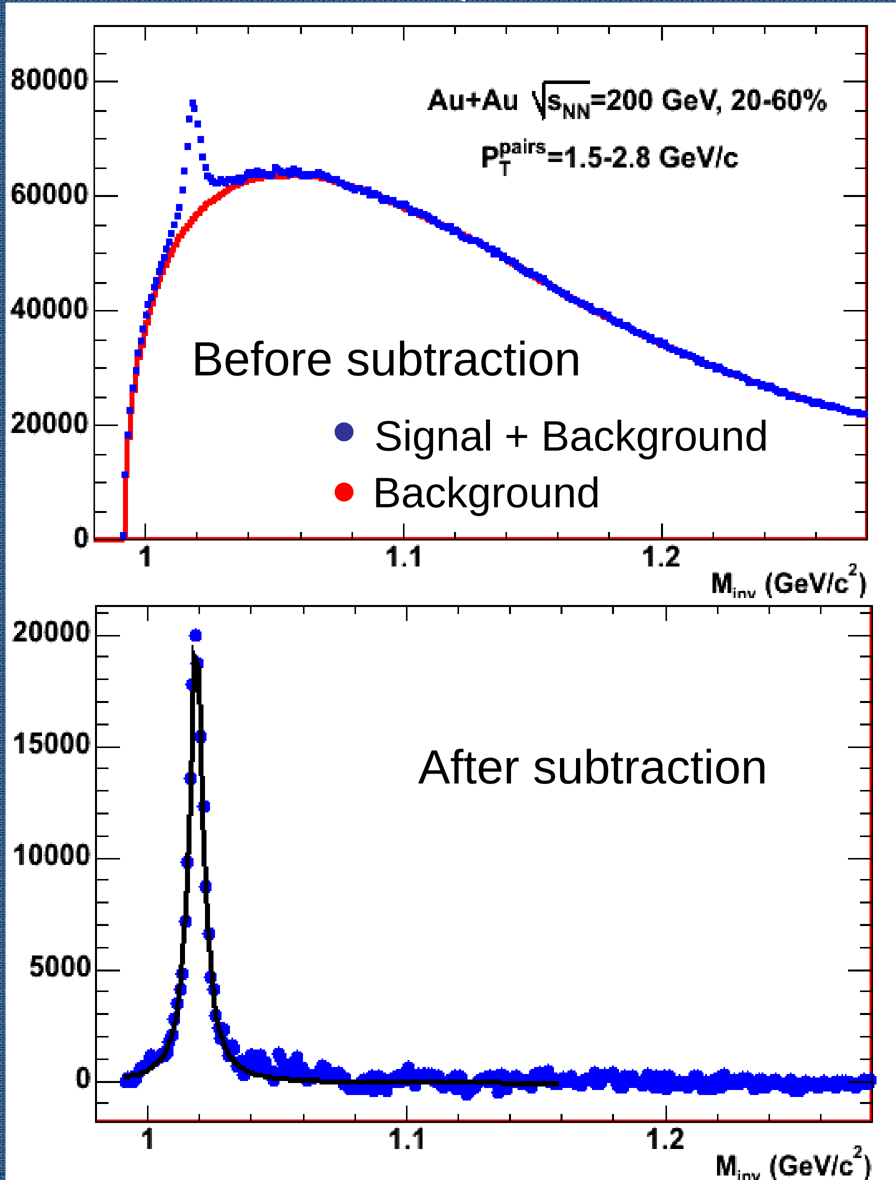
What can we learn from identified hadrons ?



QM2005, M. Oldenburg, STAR

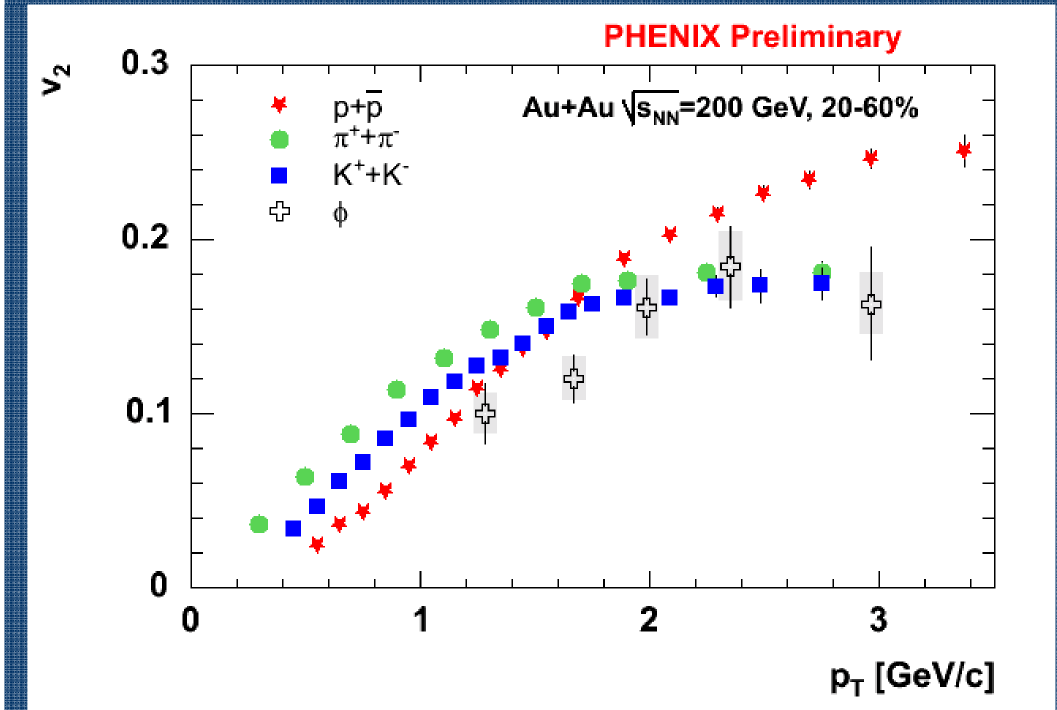
- NCQ (Number of Constituent Quark) scaling of v_2 indicate partonic collectivity at RHIC
- ϕ meson is a good probe to test NCQ scaling
  - No re-scattering in hadronic stage
  - Longer life time ~ 40 fm/c
  - Thermal s-quark coalesce/recombine to form ϕ meson

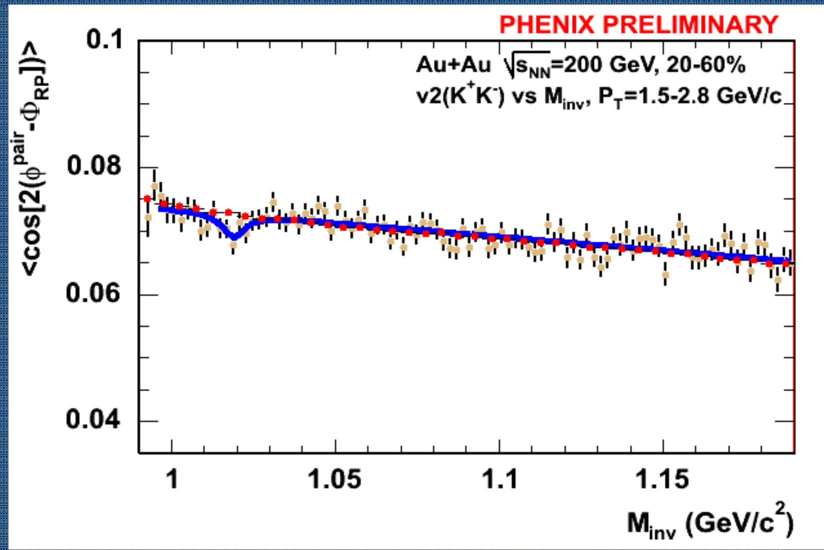
Clear ϕ signal



- $\phi \rightarrow K^+K^-$
  - Typical S/N ~ 0.3
- Centrality 20 – 60 %
  - S/N is good
  - Event plane resolution is good
  - Separation of v_2 between meson and baryon is good
  - Magnitude of v_2 do not vary very much

ϕ Meson v_2



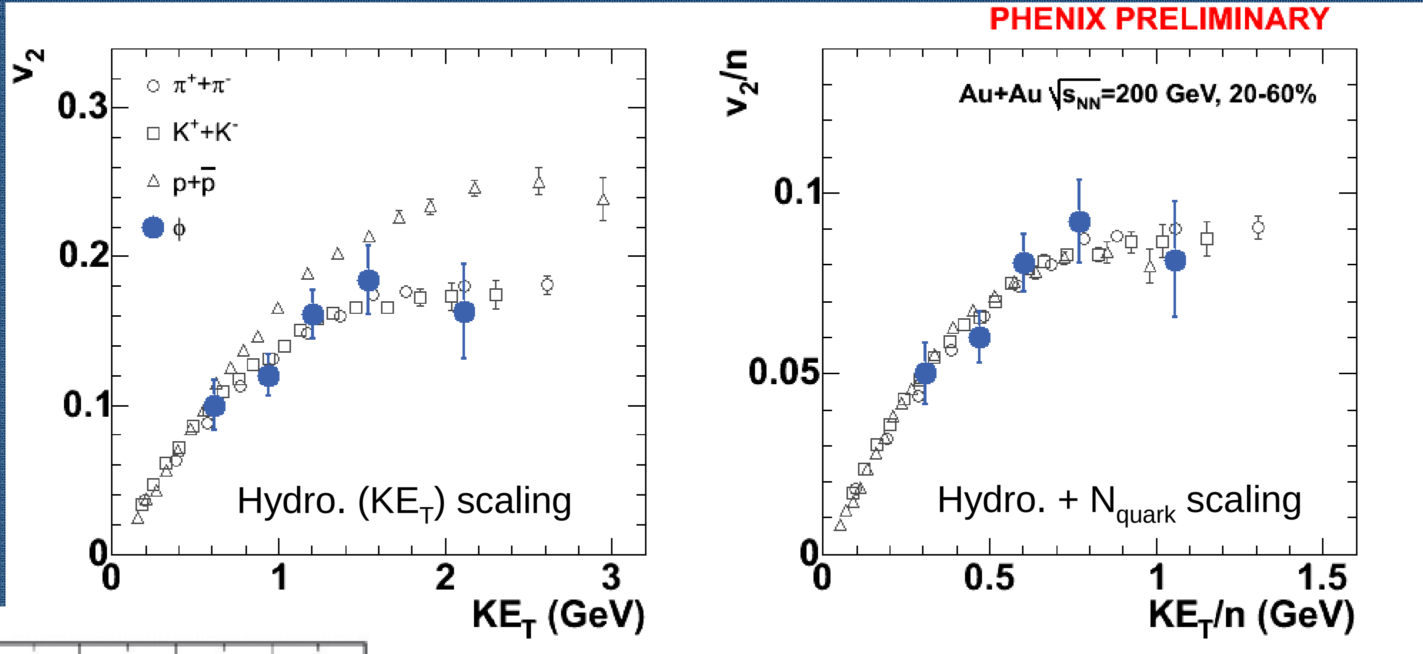


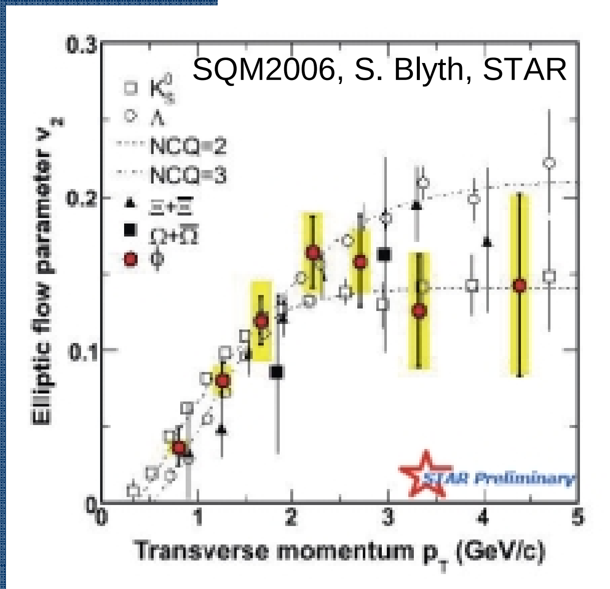
$$v_2^{measured} = \frac{N_S v_2^S + N_B v_2^B}{N_S + N_B}$$

N. Borghini, J.-Y. Ollitrault, PRC 70, 064905 (2004)

- Obtained from invariant mass fit method
  - Consistent with standard subtraction method
  - Smaller systematic error
- $p_T < 2$ GeV/c
  - Consistent with mass ordering from hydrodynamics

Partonic Collectivity (i)

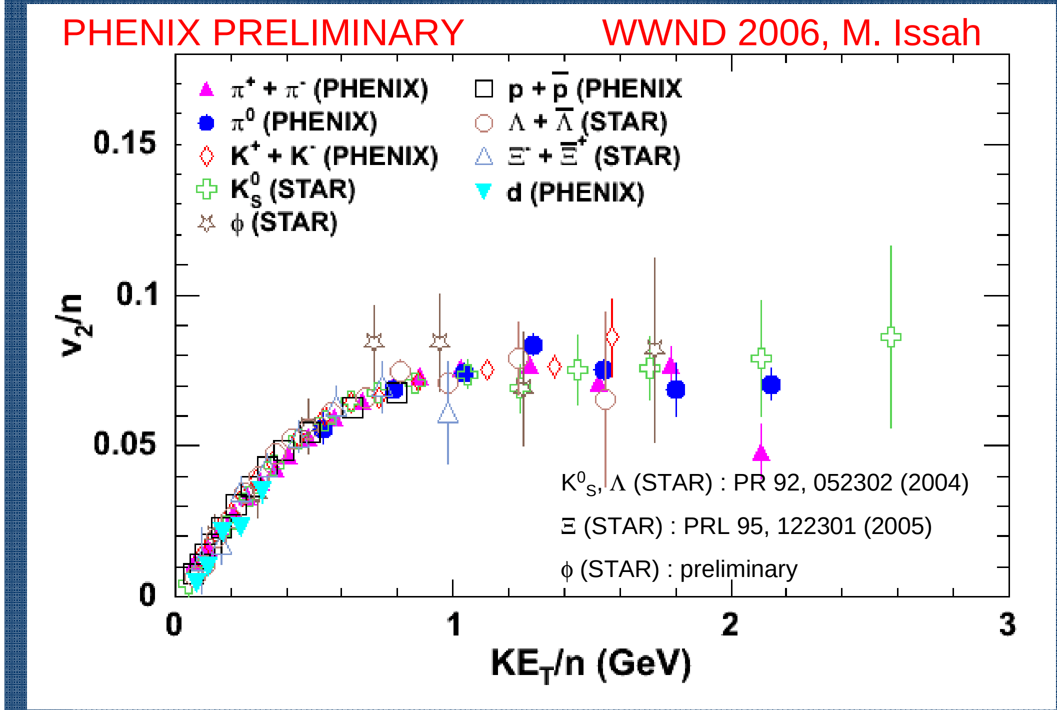




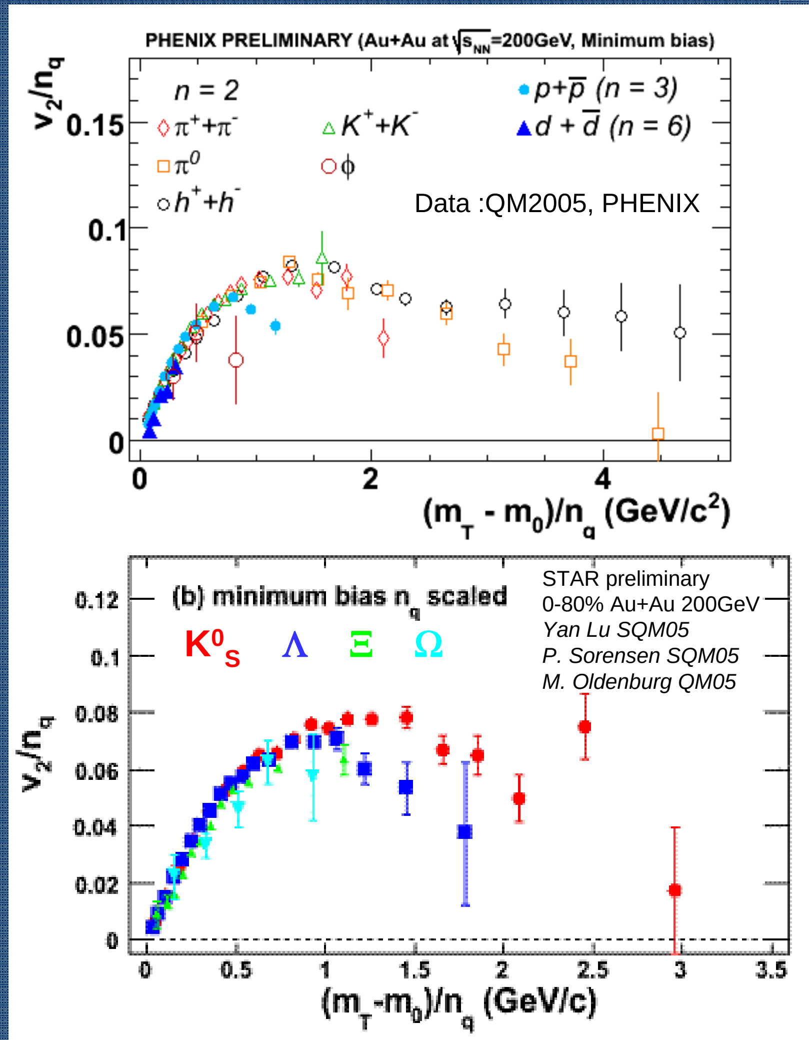
- Hydro + NCQ scaling works for ϕ meson
  - STAR result favors NCQ=2 for ϕ
  - Consistent with other multi-strange hadrons (Ω, Ξ) from STAR

→ Collective flow of s-quark

Partonic Collectivity (ii)



SQM2006, S. Esumi



- Hydro + NCQ scaling describes v_2 for a variety of particles measured at RHIC
  - Scaling breaks for higher p_T

Summary

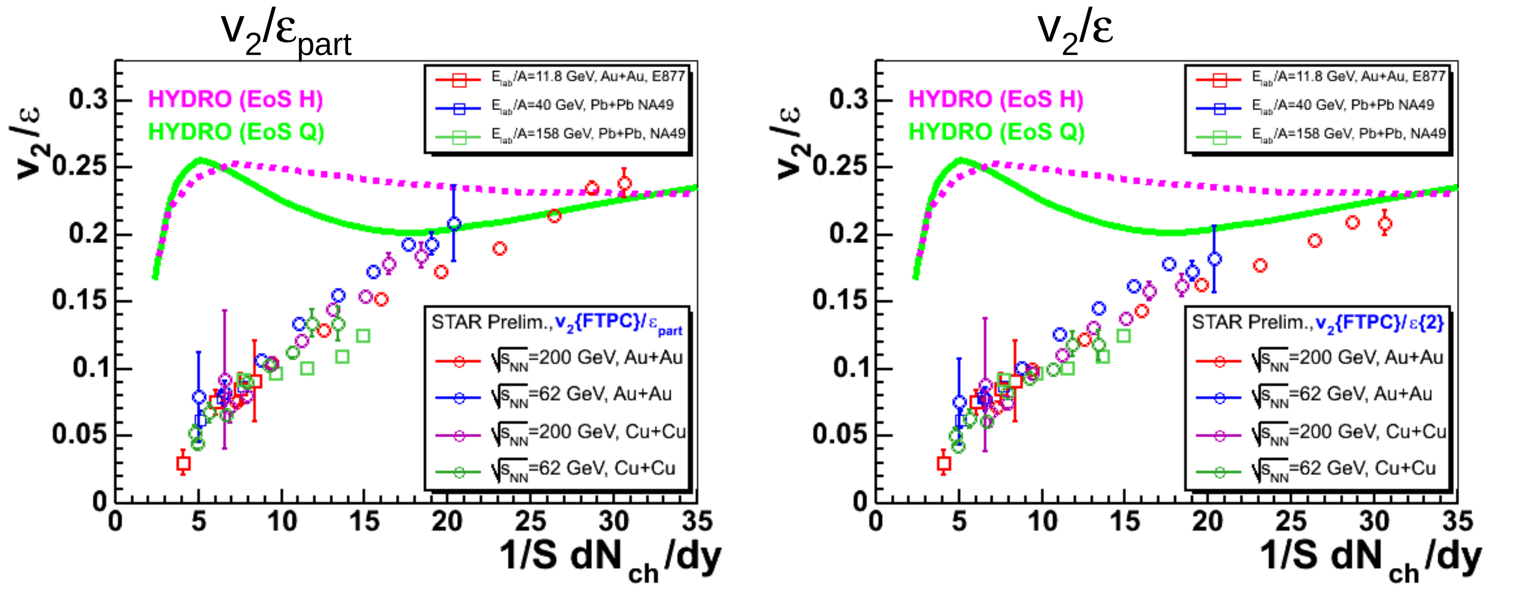
PHENIX

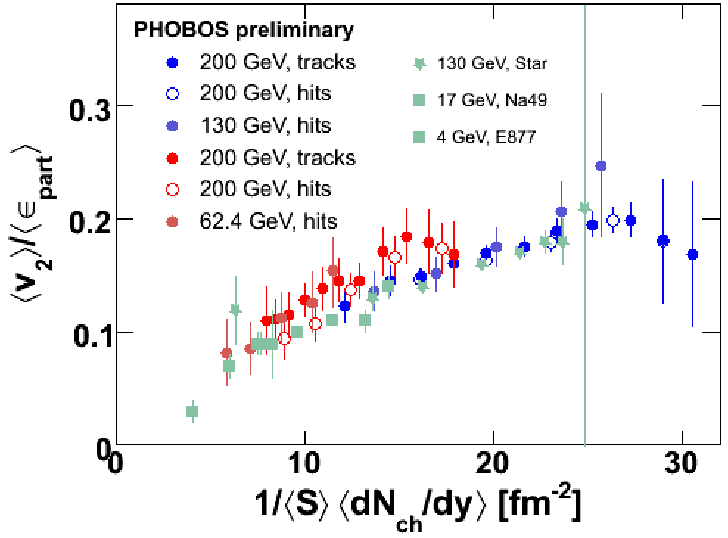
- What have we learned from anisotropic flow + hydrodynamics at RHIC ?
- Strongly interacting partonic matter
  - Large v_2 → Early thermalization, $\tau < 1$ fm/c
  - v_2 scales eccentricity, independent of system size (Au, Cu)
    - Estimated speed of sound = 0.35 ± 0.05
  - Partonic Collectivity
    - Kinetic energy + NCQ scaling works for a broad set of particles
- What more can be learned ?
  - Centrality, energy dependence of v_2
  - $v_4/(v_2)^2$ as a probe for degree of thermalization
- PHENIX talks in this session
  - 2:25 PM : S. Sakai, heavy flavor electron v_2
  - 4:20 PM : J. Newby, HBT

Thank you

Back up

v_2/ε, STAR, PHOBOS





CIPANP 2006, S. Voloshin, STAR
QM2005, S. Manly, PHOBOS

- $v_2/\varepsilon \sim 0.1 - 0.2$