Beam Energy Scan Results from PHENIX Experiment

Arkadiy Taranenko

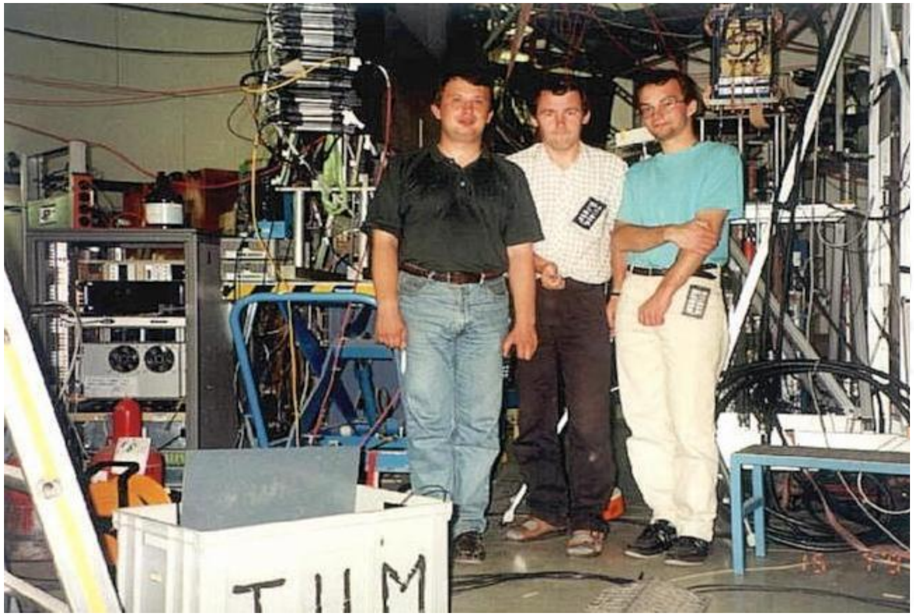
National Research Nuclear University MEPhI
(Moscow Engineering Physics Institute)

for the PHENIX Collaboration

Physics Symposium during the 26th CBM Week

Masarykov kolej, Prague, September 16, 2015

Thanks a lot to Andrej Kugler , Pavel Tlusty and Vladimir Wagner for the introduction to the physics of collective flow



Q·B·F·F·F·Q·S
SUMMIS AUSPICIIS REI PUBLICAE BOHEMICAE
UNIVERSITAS CAROLINA PRAGENSIS
NOS RECTOR UNIVERSITATIS
ET DECANUS FACULTATIS MATHEMATICAE PHYSICAEQUE DISCIPLINAE
TENOREM OMNIUM QUAE SEQUUNTUR RATUM PRAESTAMUS LECTURIS
ING. ARKADIJ TARANĚNKO
NATUS DIE 1.4.1971 IN CIVITATE MOSKVA
ORDINE STUDIORUM DOCTORIS PROPRIO QUI
Physica
NUNCUPATUR IN DISCIPLINA
Physica nuclearis
IN FACULTATE MATHEMATICAE PHYSICAEQUE DISCIPLINAE
DILIGENTER SERVATO
DISSERTATIONEM EXHIBUIT EXAMINAQUE DOCTORI PUBLICE PRAECEPTA SUBIIT
QUAM OB REM IUXTA LEGEM N. 111/1998 LEG. COL.
NOMEN ACADEMICUM
DOCTORIS
EI TRIBUTUM EST
QUOD IN „Ph.D.“ CONTRACTUM COGNOMINI EIUS RITE ADICIATUR
IN CUIUS REI TESTIMONIUM HOC DIPLOMA FIERI IUSSIMUS

PROF. ING. IVAN WILHELM, CSC.
RECTOR

Michal Suk
PROF. RNDR. MICHAL SUK, DRSC.
PROMOTOR RITE CONSTITUTUS

PROF. RNDR. IVAN NETUKA, DRSC.
DECANUS

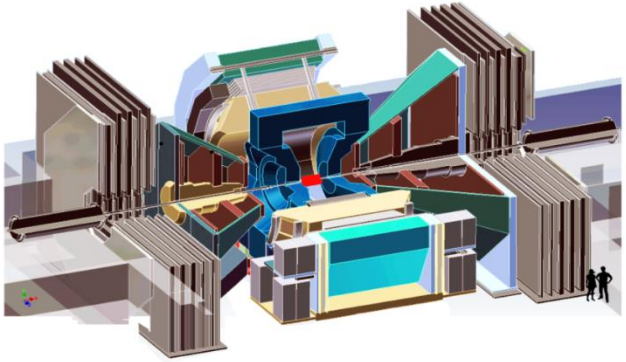
DATUM PRAGAE DIE XVIII MENSIS MAII ANNI MMI

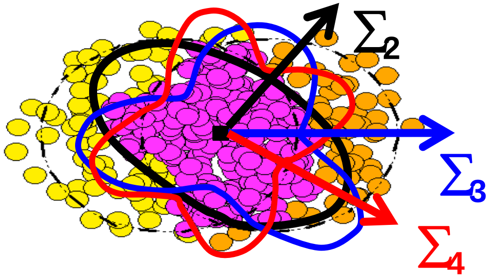
NUM. 1326

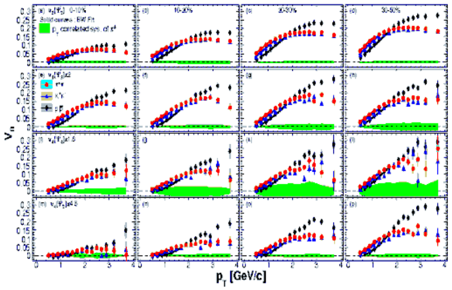
2001: “Elliptic flow of η and π⁰ mesons in relativistic heavy-ion collisions at 2 A GeV”

Beam Energy Scan Results from PHENIX

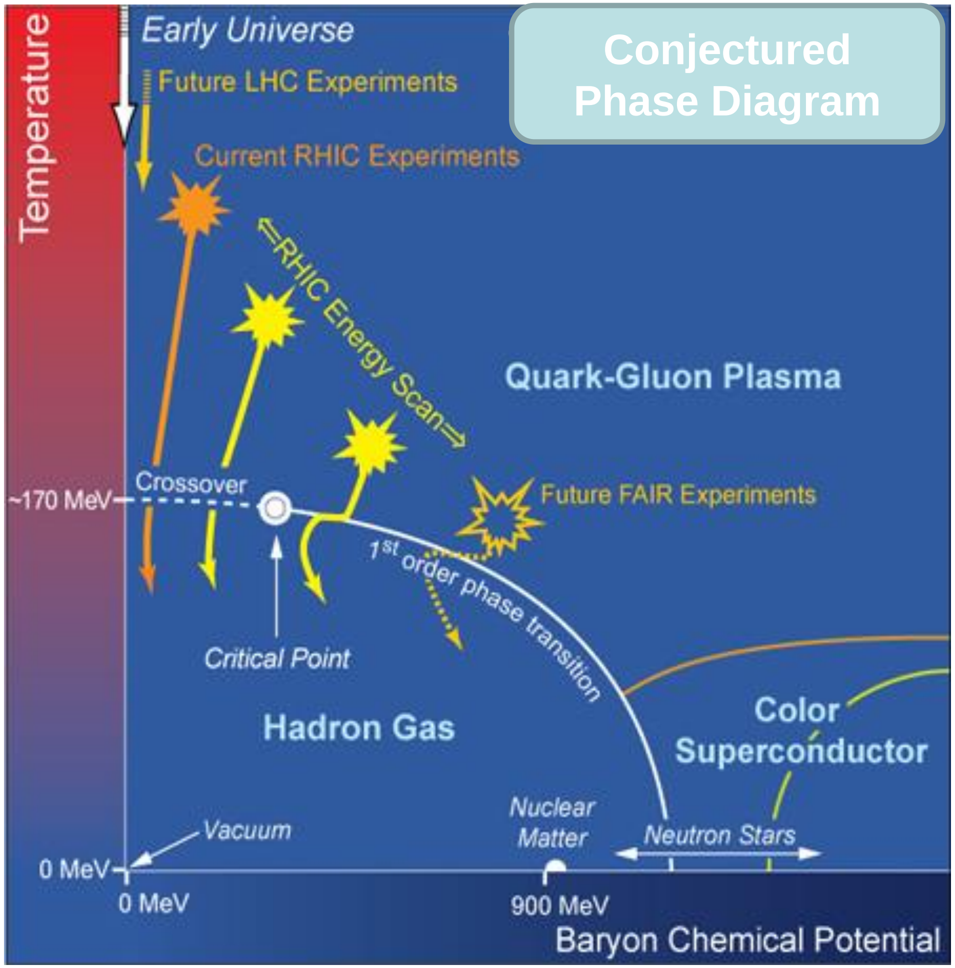
1) Introduction
2) PHENIX Experiment at RHIC
3) Methods : V_n measurements and HBT correlations
4) Comparison with STAR
5) Scaling properties of flow and correlations at RHIC
6) System size and beam energy dependence of correlations
7) Correlations in small systems: d+Au and ^{3}He+Au at 200GeV
8) Conclusions and Outlook

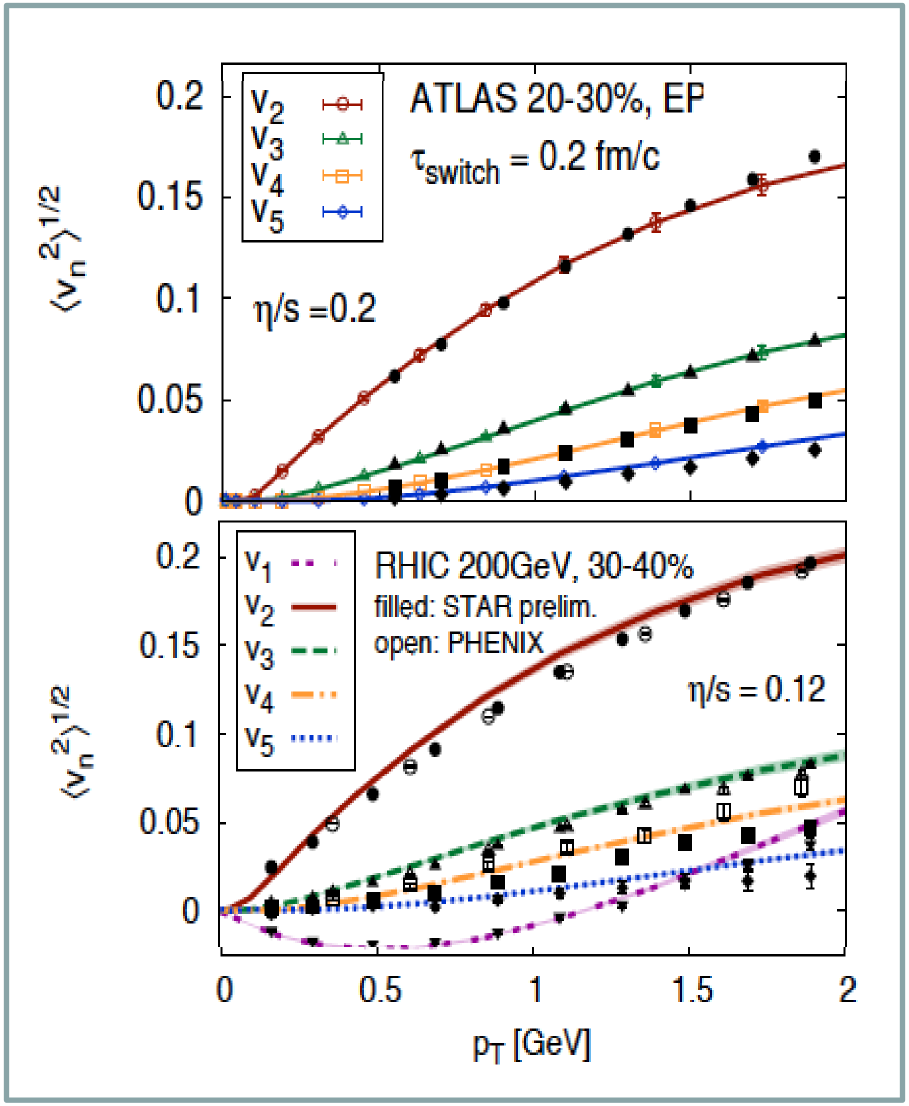






2015: 10 years of the "perfect fluid" found at RHIC

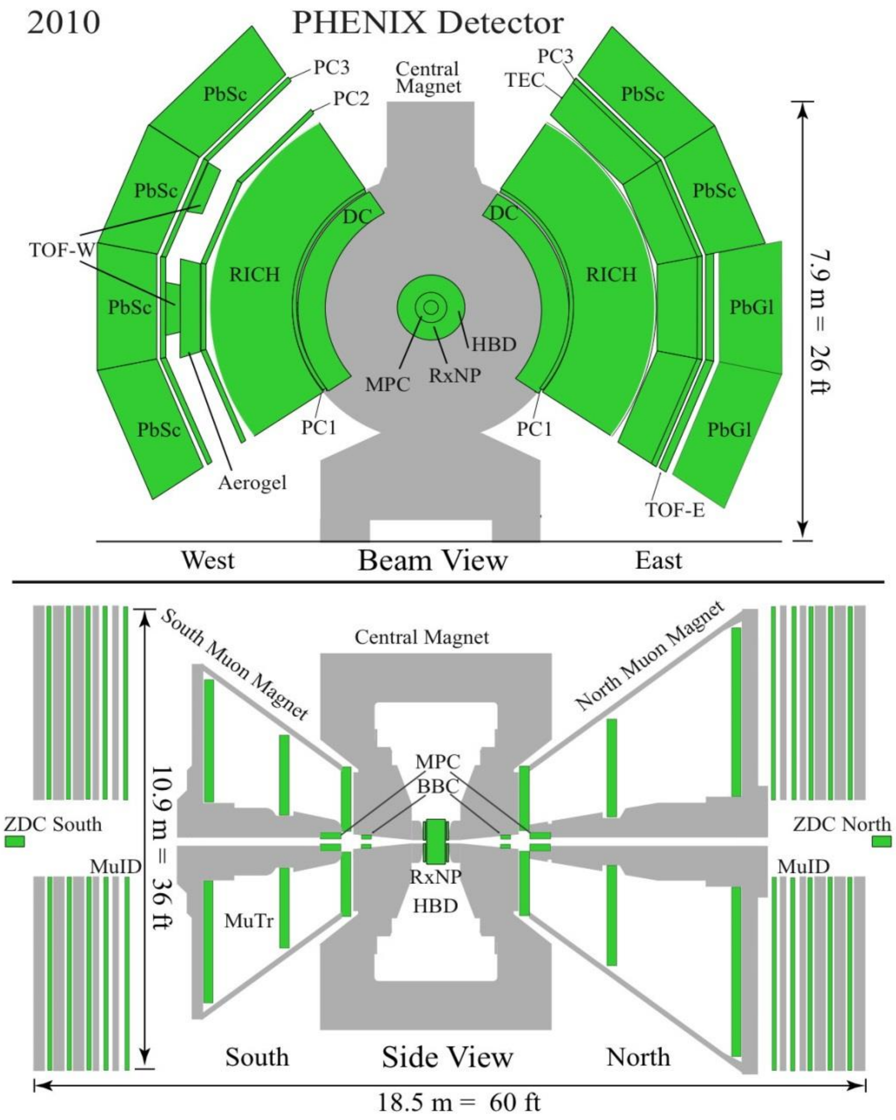


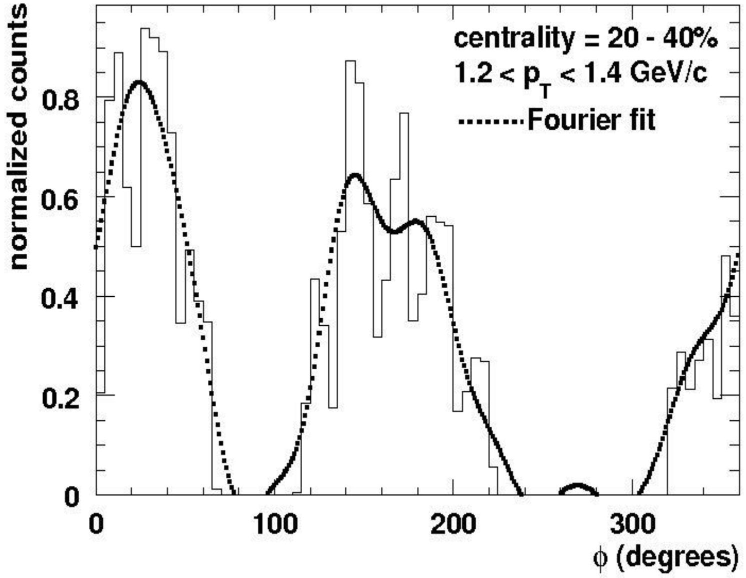


The Crossover is a necessary requirement for existence the CEP

Calculation from Bjoern Schenke

PHENIX spectrometer at RHIC



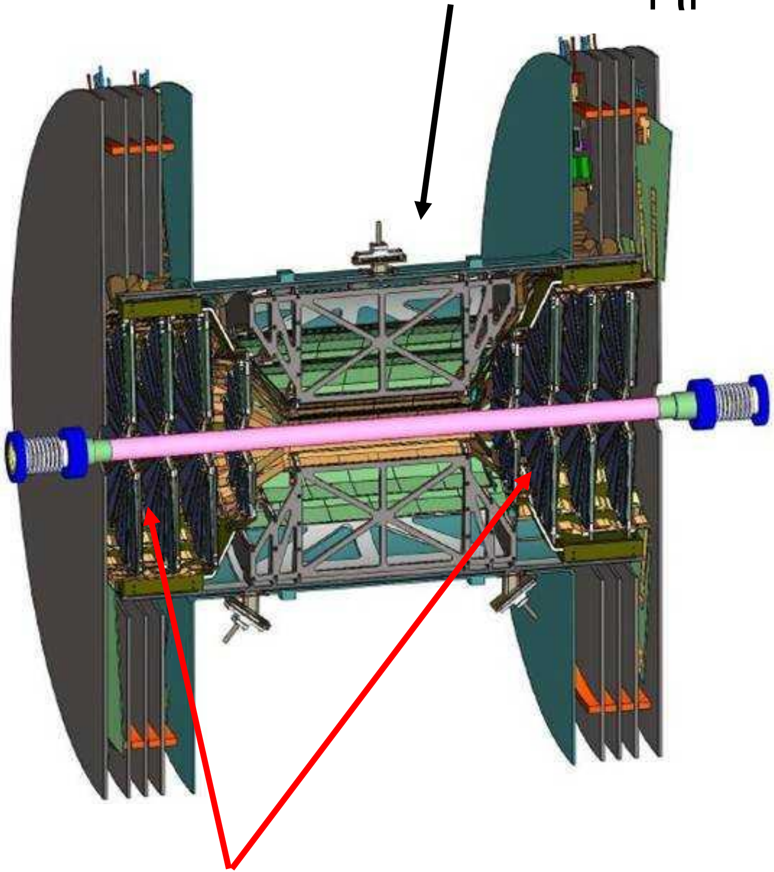


2007 Au+Au 200 GeV

2010 Au+Au 62.4 GeV, 39 GeV, 7.7 GeV

Focus on two particle correlations: flow and HBT

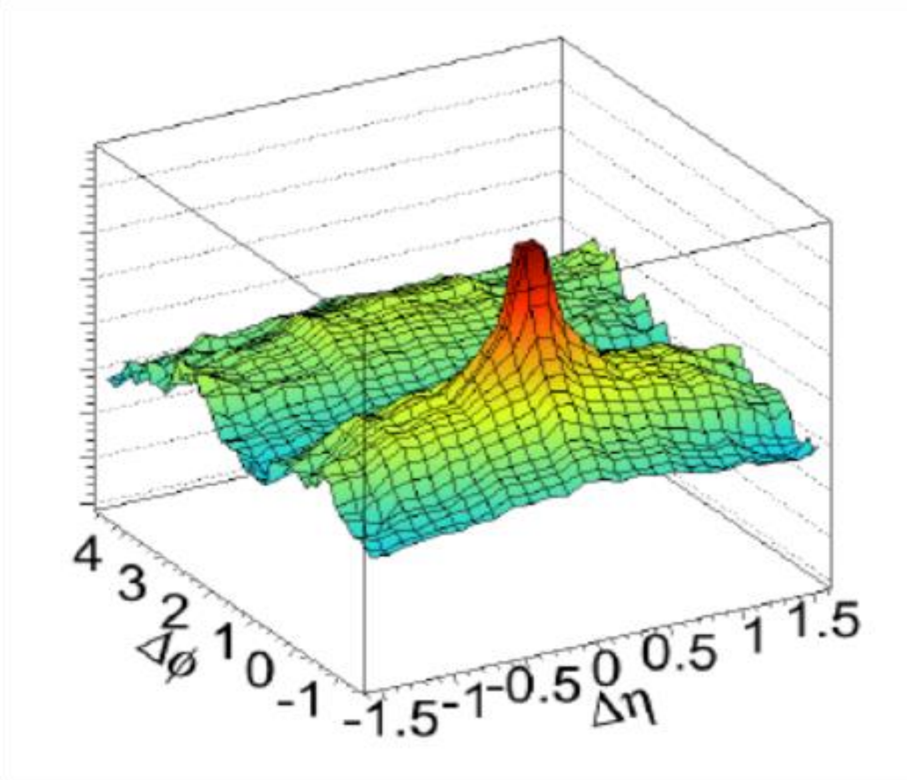
PHENIX Silicon Vertex (VTX & FVTX)



VTX barrel $|\eta|<1.2$

FVTX endcaps
$1.5<|\eta|<3.0$
mini strips

2014 ^{3}He+Au at 200GeV

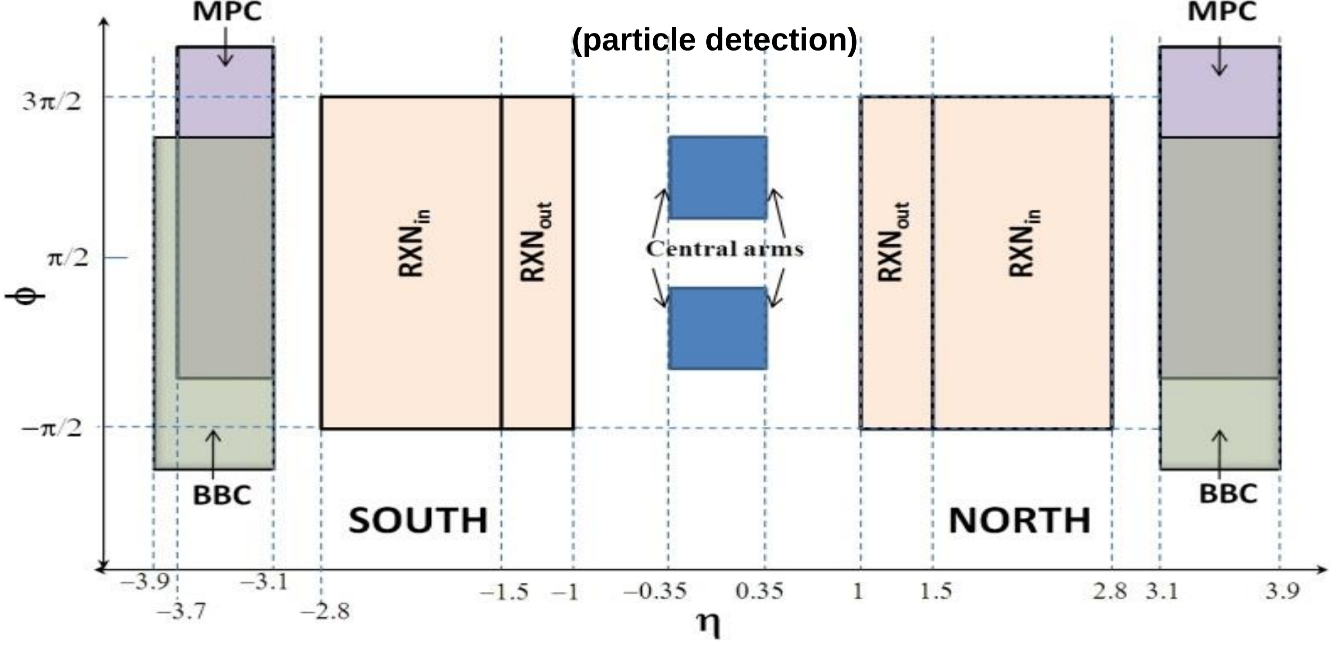


2011 Au+Au 27 GeV, 19.6 GeV
2012 Cu+Au 200 GeV
2014 Au+Au 14.5 GeV, ^{3}He+Au at 200GeV

PHENIX Flow Measurements : Methods

Central Arms (CA) |η'| < 0.35

(particle detection)



ψ_n RXN (|η|=1.0~2.8)

MPC (|η|=3.1~3.7)

BBC (|η|=3.1~3.9)

From 2012:

- FVTX (1.5<|η|<3)

Correlate hadrons in central Arms

with event plane (RXN, etc)

$$\frac{dN}{d\varphi} \propto \left(1+2\sum_{n=1}^{+\infty} v_n \cos[n(\varphi-\psi_n)]\right) \qquad \textbf{(I)}$$

$$v_n\{\psi_n\} = \left\langle \cos\left[n\left(\varphi-\psi_n\right)\right]\right\rangle, \quad n=1,2,3..,$$

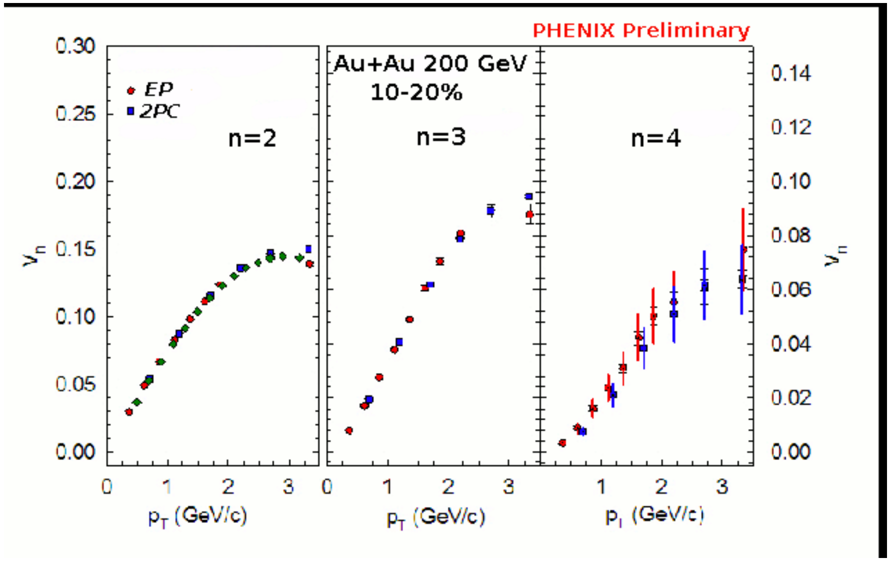
- ***Δφ correlation function for EP$_N$ - EP$_S$***

$$\frac{dN^{\text{pairs}}}{d\left(\Delta\varphi\right)} \propto \left(1+\sum_{n=1} 2v_n^a v_n^b \cos(n\Delta\varphi)\right) \qquad \textbf{(II)}$$

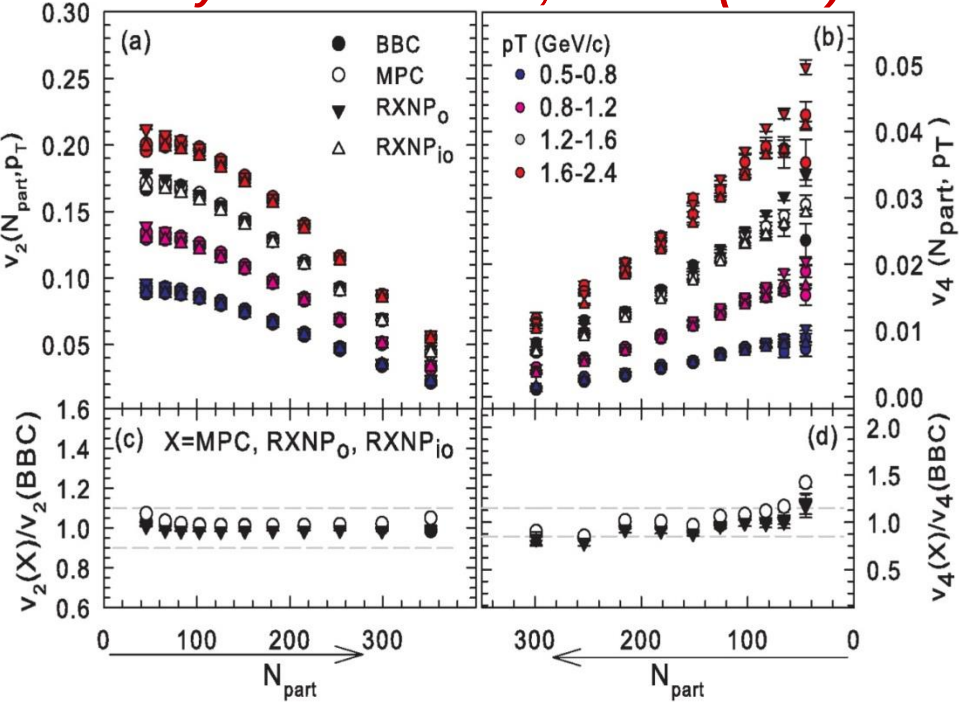
- ***Δφ correlation function for EP - CA***

PHENIX Flow Measurements : Methods

V_n (EP): ***Phys.Rev.Lett. 107 (2011) 252301***



Phys. Rev. Lett. 105, 062301 (2010)



- ***Good agreement between V_n results obtained by event plane (EP) and two-particle correlation method (2PC)***

- ***No evidence for significant η-dependent non-flow contributions from di-jets for pT=0.3-3.5 GeV/c.*** **Systematic uncertainty : event plane: 2-5% for v2 and 5-12% for v3.**

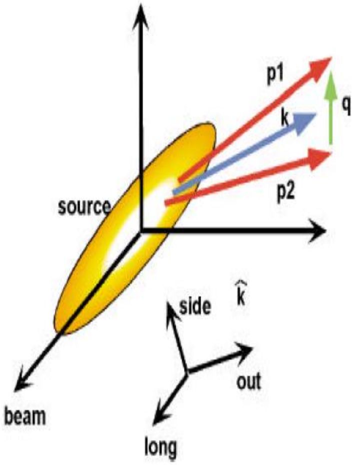
Ψ_n^{RXN} (|η|=1.0~2.8)

^{MPC} (|η|=3.1~3.7)

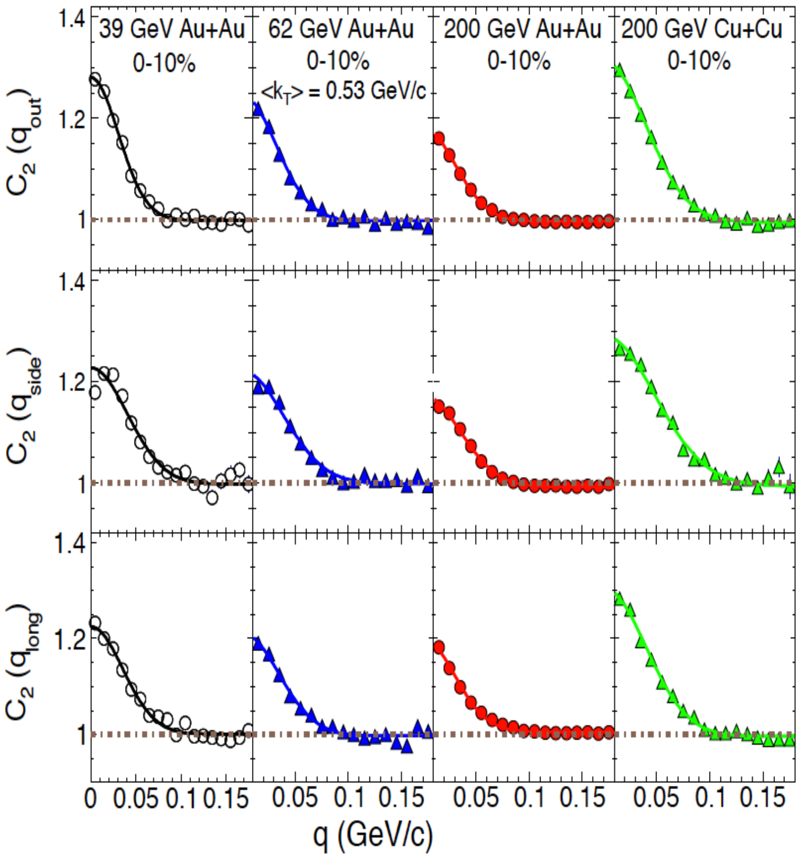
^{BBC} (|η|=3.1~3.9)

arXiv:1412.1038 , arXiv:1412.1043

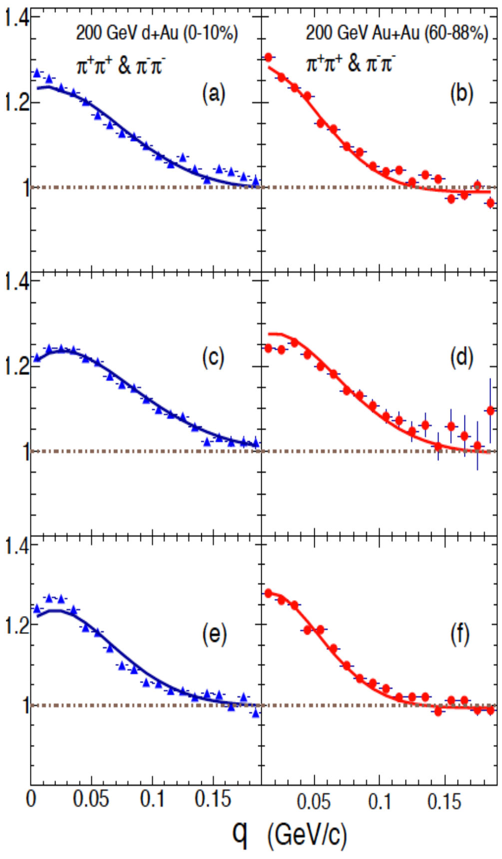
PHENIX: 3D 2π HBT correlation functions



arXiv: 1410.2559 [nucl-ex]



arXiv:1404.5291



- **3D Gaussian fits**
- **Bertsch-Pratt coord.**
- **LCMS ($p_{1z}+p_{2z}=0$)**
- **Coulomb Corrected**

$q = p_2 - p_1$
$k_T = |p_{T2} + p_{T1}|/2$

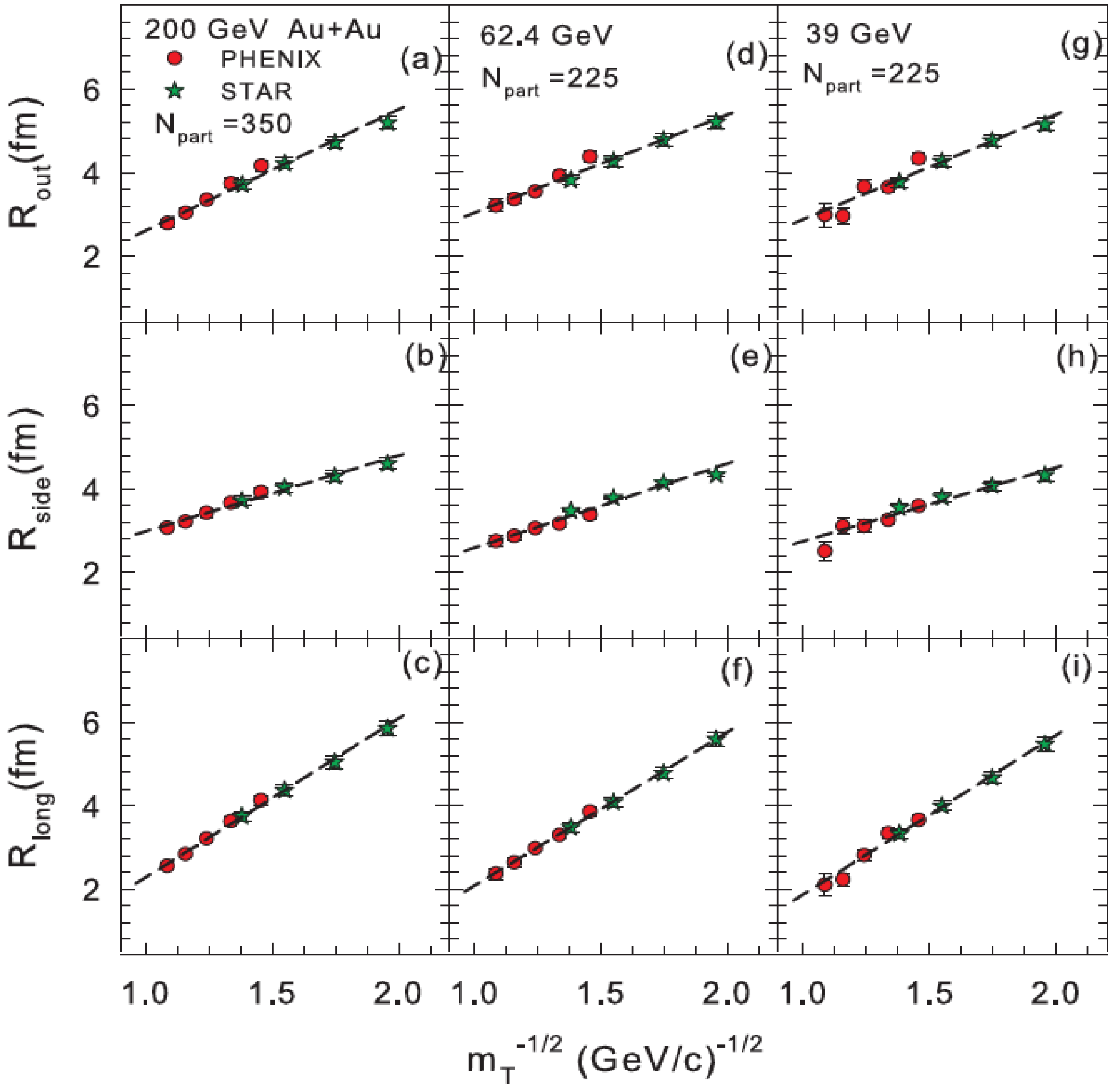
$$C_2(\mathbf{q}) = N[(\lambda(1 + G(\mathbf{q})))F_c + (1 - \lambda)]$$

$$G(\mathbf{q}) \cong \exp(-R_{\mathrm{side}}^2 q_{\mathrm{side}}^2 - R_{\mathrm{out}}^2 q_{\mathrm{out}}^2 - R_{\mathrm{long}}^2 q_{\mathrm{long}}^2)$$

broader width ⟶ smaller HBT radius

Comparison of PHENIX vs STAR 3D 2π HBT Radii

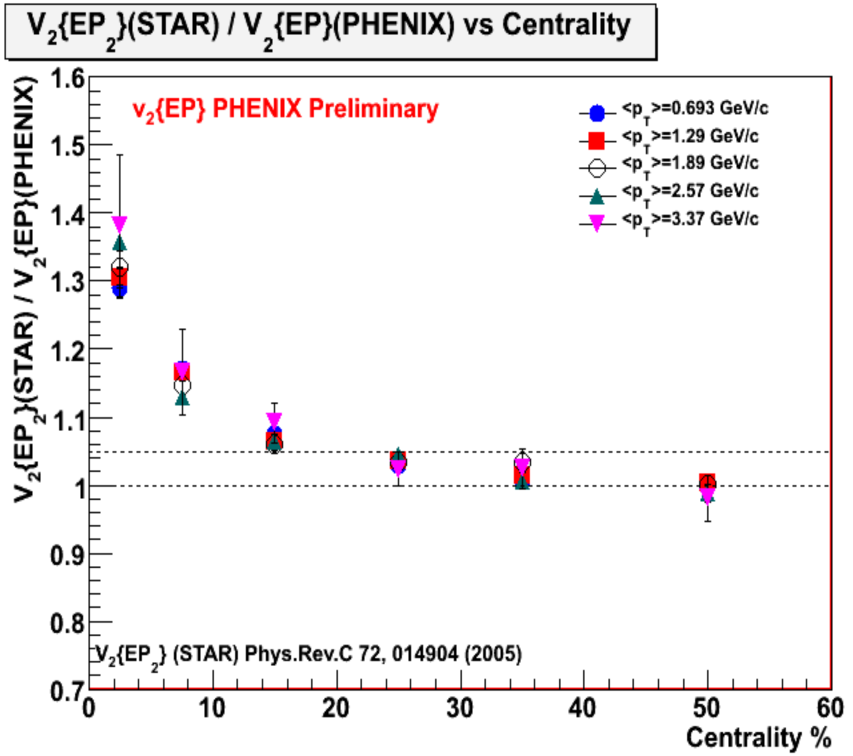
arXiv: 1410.2559 [nucl-ex]

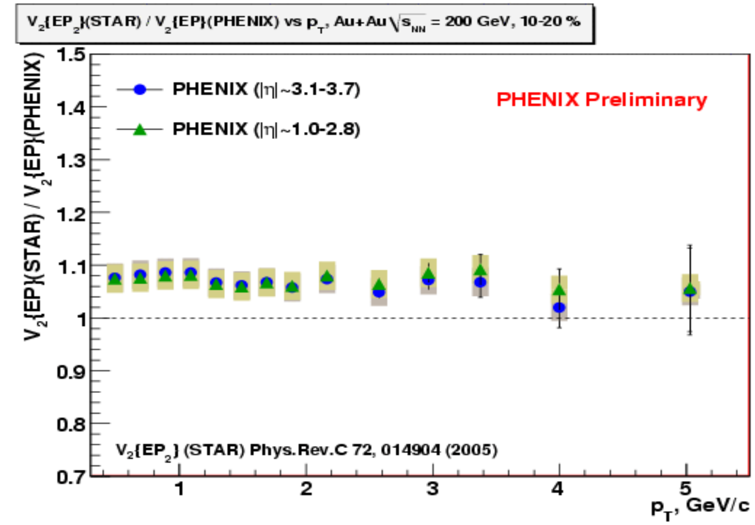


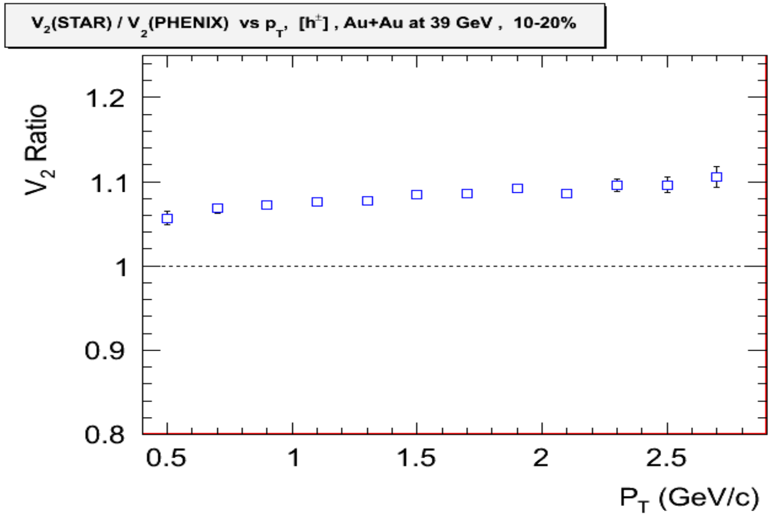
STAR data from arXiv:1403.4972 [nucl-ex]

- agreement between PHENIX and STAR data sets
- all radii linear
  - $R_i = a + b/\sqrt{m_T}$
- sizable extension in m_T range from the combined data sets
- combine the data sets to construct excitation functions for HBT radii

Comparison of PHENIX vs STAR: v2 at 39-200 GeV





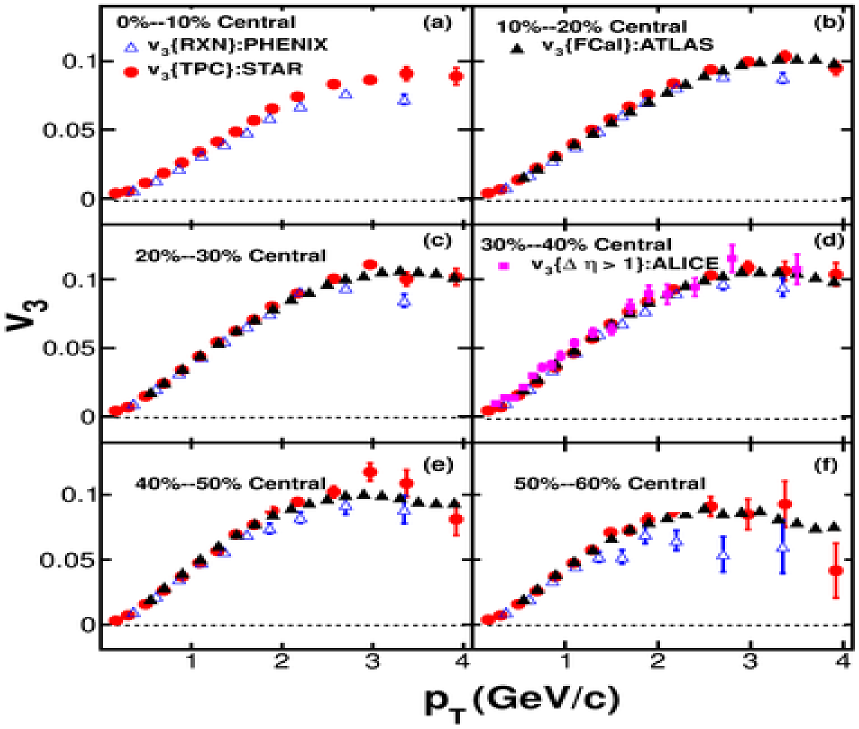


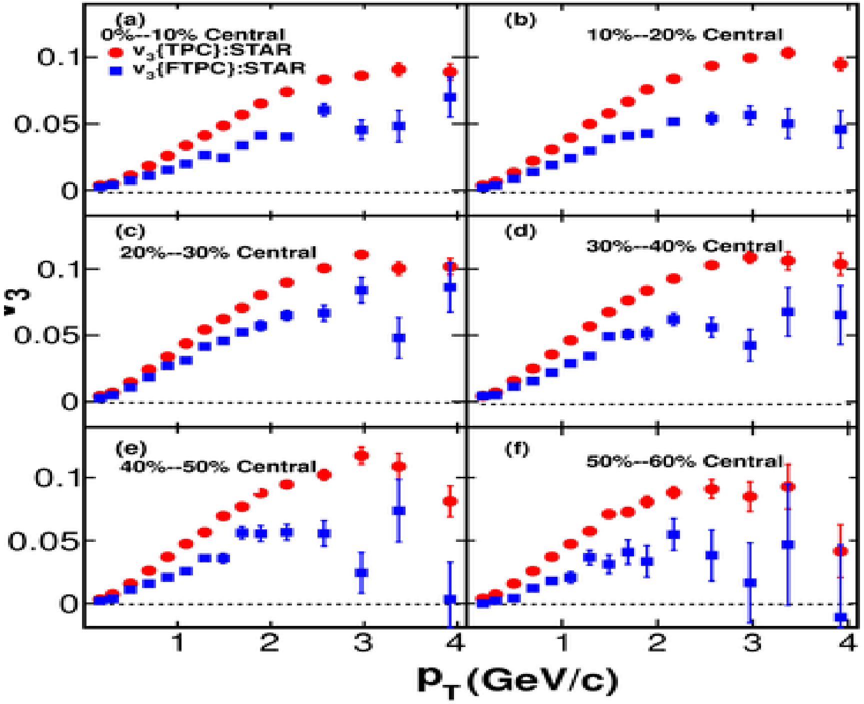
For 0-20% central collisions STAR V_2 > PHENIX V_2 : do we have the same centrality definition between experiments?

V3 in Au+Au at 200 GeV (STAR/PHENIX)

STAR: Third Harmonic Flow of Charged Particles in Au+Au Collisions at 200 GeV

Phys. Rev. C **88** (2013) 14904





Do we understand the difference in v3 measurements between STAR and PHENIX ?

Scaling properties of flow and correlations

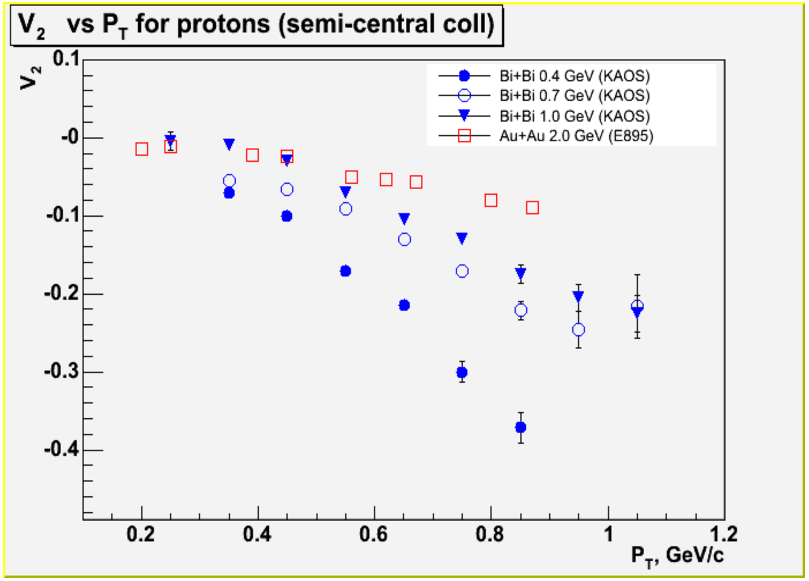
"Change of collective-flow mechanism indicated by scaling analysis of transverse flow " A. Bonasera, L.P. Csernai , Phys.Rev.Lett. 59 (1987) 630-633

The general features of the collective flow could, in principle, be expressed in terms of scale-invariant quantities. *In this way the particular differences arising from the different initial conditions, masses, energies, etc. , can be separated from the general fluid-dynamical features. . …. Deviations from such an ideal scaling signal physical processes which lead to a not-scale-invariant flow, like special properties of the equation of state (EOS), potential energy, or phase transitions, dissipation, relativistic effects, etc.*

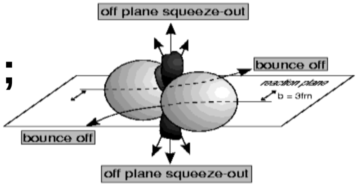
"Collective flow in heavy-ion collisions", W. Reisdorf, H.G. Ritter Ann.Rev.Nucl.Part.Sci. 47 (1997) 663-709 :

There is interest in using observables that are both coalescence and scale-invariant. *They allow comparison with theories that are limited to making predictions for single-particle observables. Under certain conditions the evolution in nonviscous hydrodynamics does not depend on the size of the system nor on the incident energy, if distances (such as impact parameters) are rescaled (reduced) in terms of a typical size parameter, such as the nuclear radius. Velocities, momenta and energies are rescaled in terms of the beam velocities, momenta or energies.*

Scaling properties of flow at SIS



(KAOS – Z. Phys. A355 (1996);
(E895) - PRL 83 (1999) 1295

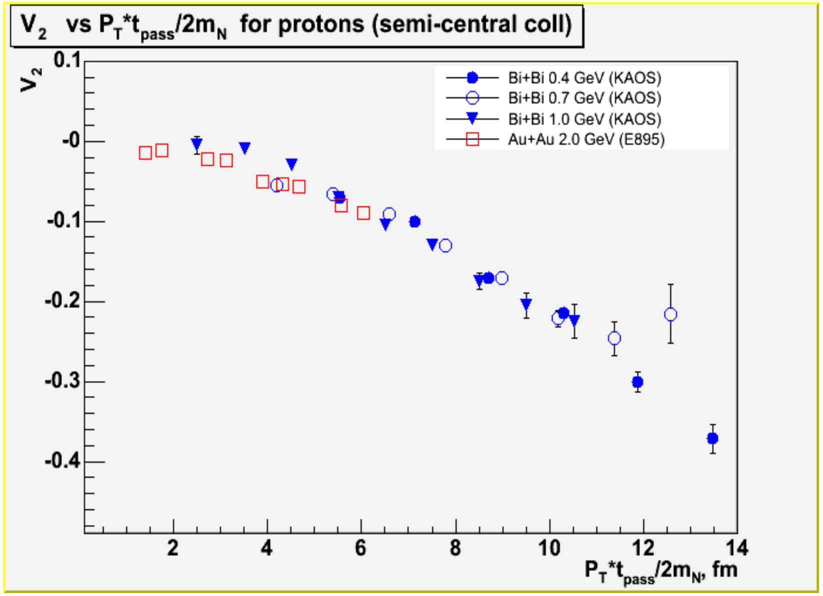


Interplay of passage/expansion times

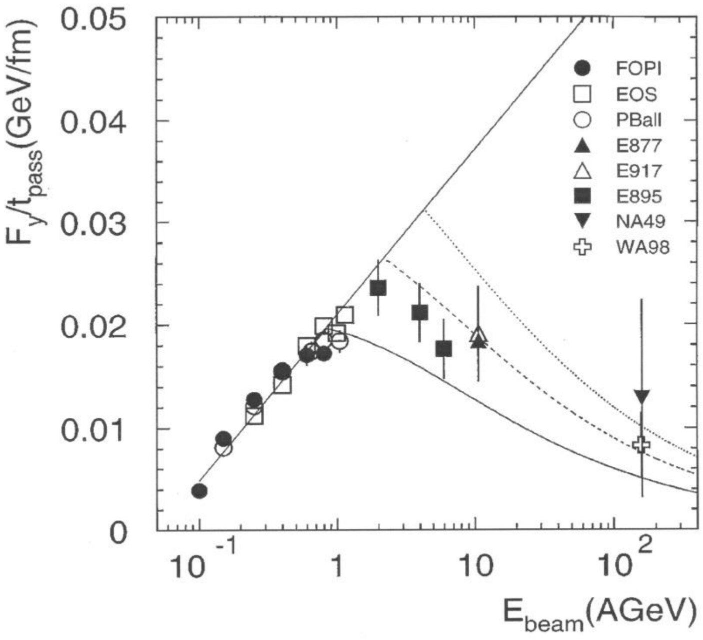
Passage time: $2R/(\beta_{cm}\gamma_{cm})$

Expansion time: R/c_s

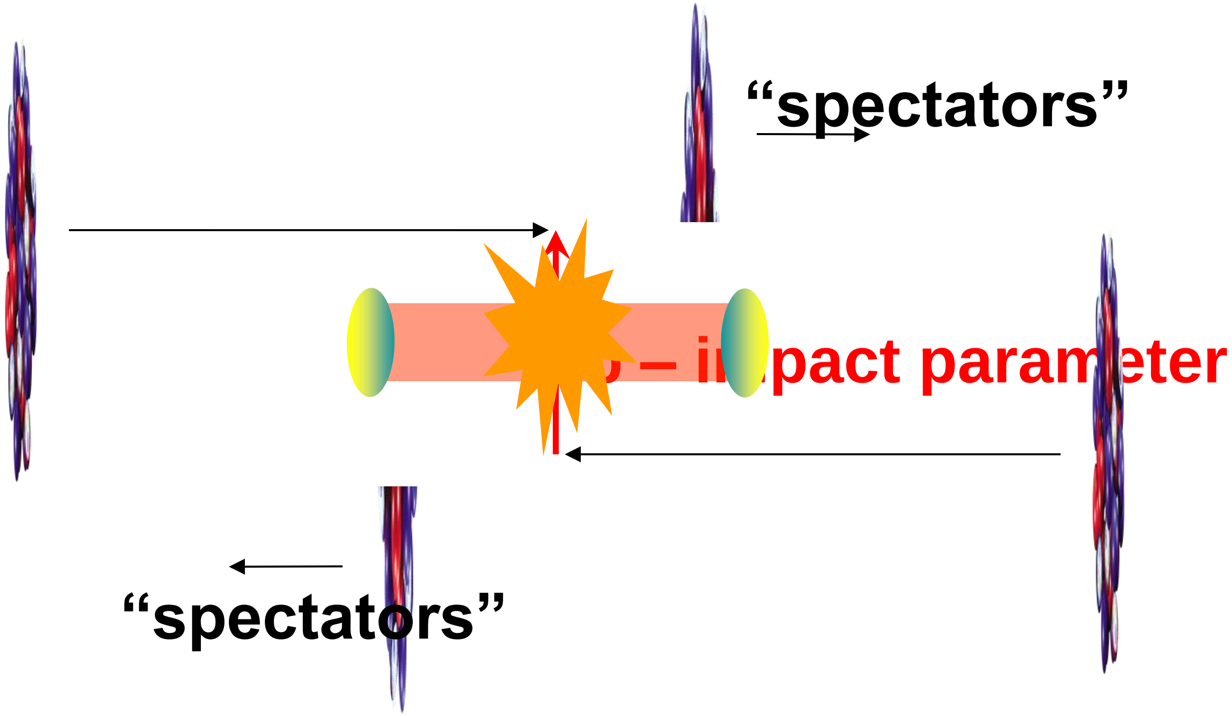
$c_s = c\sqrt{dp/d\varepsilon}$ - speed of sound



Annu. Rev. Nucl. Part. Sci. 1999. 49:581–632



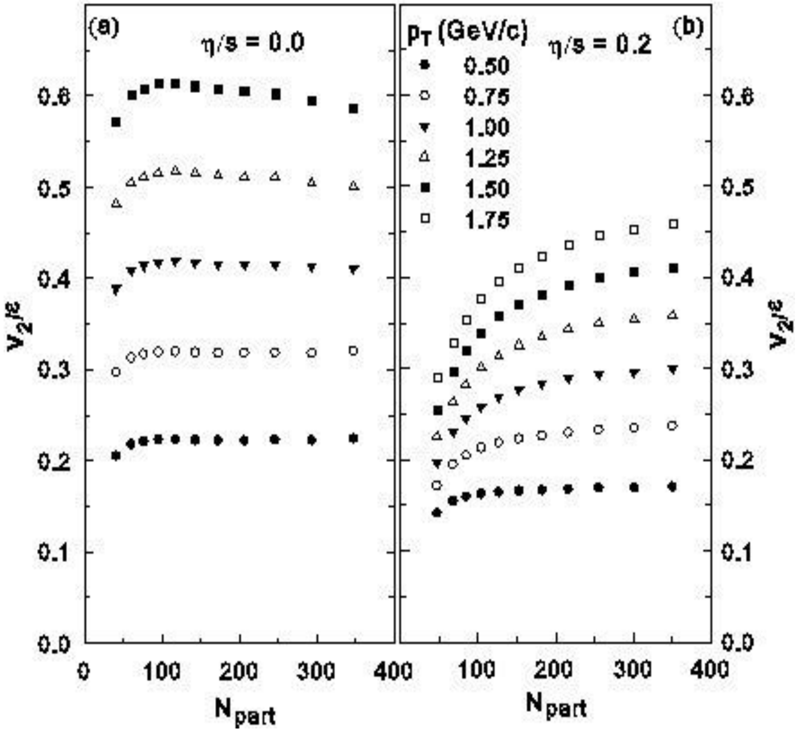
Heavy-Ion Collisions at RHIC



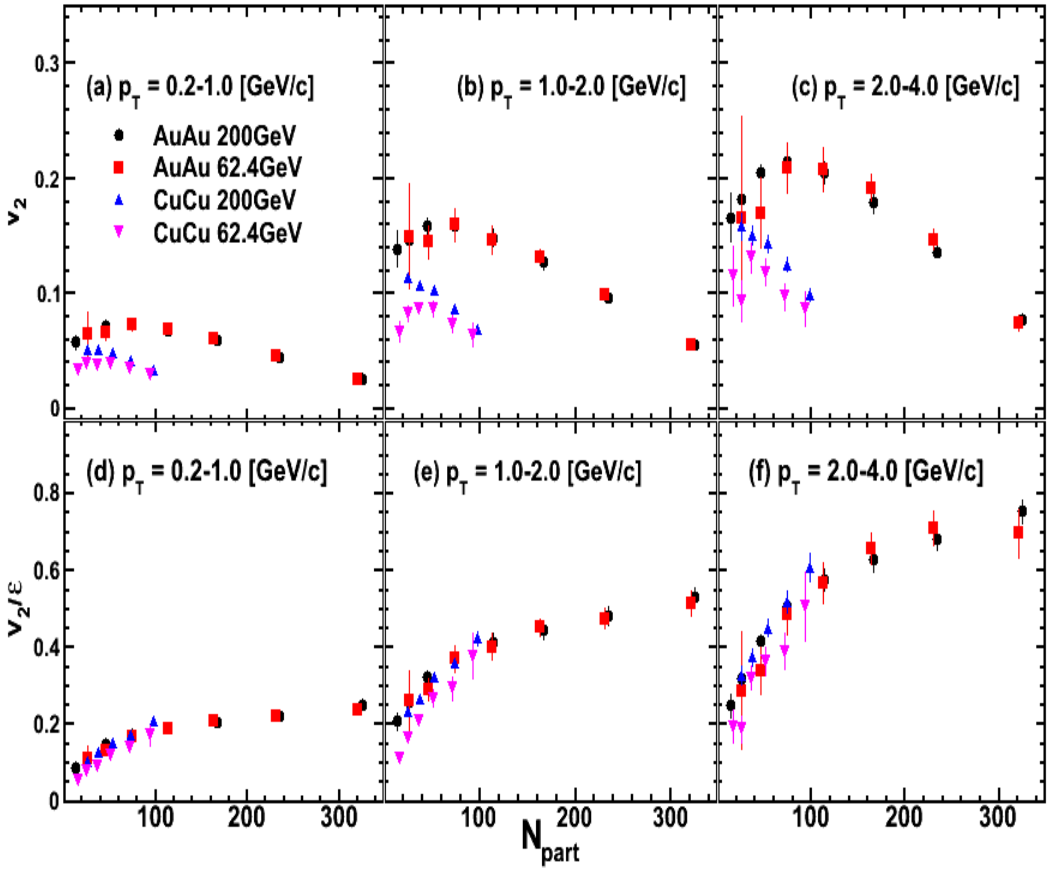
Passage time: ~ 0.15 fm/c

Centrality dependence of v2 and eccentricity scaling

Phys.Rev. C82 (2010) 034910



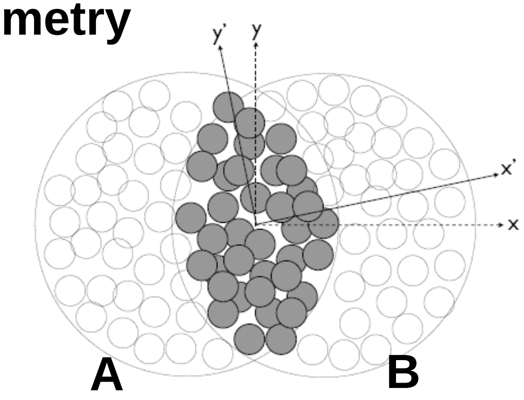
PHENIX : arXiv:1412.1043



Eccentricity scaling is broken and v2/ε depends on the Knudsen number K=λ/R̄, where λ is the mean free path and R̄ is the transverse size of the system. How viscous damping depends on the size of the colliding system / beam energy?

Geometric quantities for scaling

Geometry



Phys. Rev. C 81, 061901(R) (2010)

$$S_{nx} \equiv S_n \cos\left(n\Psi_n^*\right) = \int d\mathbf{r}_\perp \rho_s(\mathbf{r}_\perp)\omega(\mathbf{r}_\perp)\cos(n\phi)$$

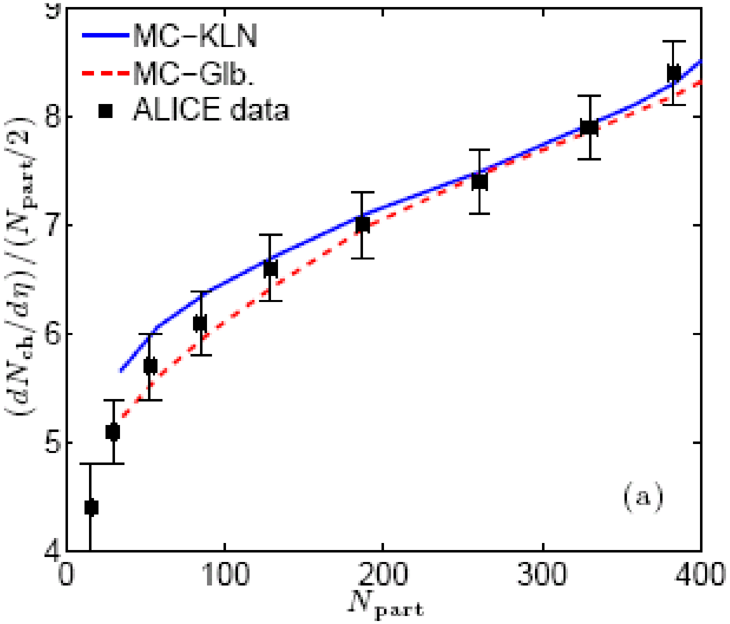
$$S_{ny} \equiv S_n \sin\left(n\Psi_n^*\right) = \int d\mathbf{r}_\perp \rho_s(\mathbf{r}_\perp)\omega(\mathbf{r}_\perp)\sin(n\phi),$$

$$\Psi_n^* = \frac{1}{n}\tan^{-1}\left(\frac{S_{ny}}{S_{nx}}\right)$$

$$\varepsilon_n = \left\langle \cos n\left(\phi - \psi_n^*\right)\right\rangle$$

arXiv:1203.3605

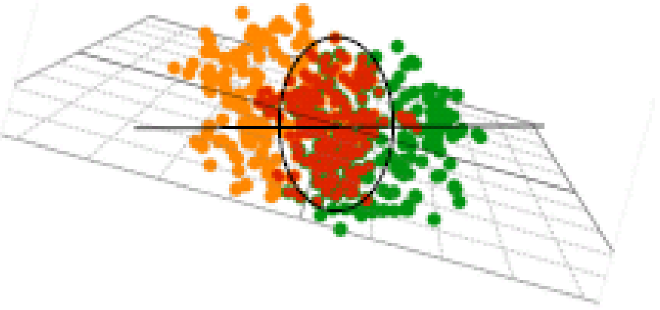
$$\frac{1}{\bar{R}} = \sqrt{\left(\frac{1}{\sigma_x^2} + \frac{1}{\sigma_y^2}\right)}$$



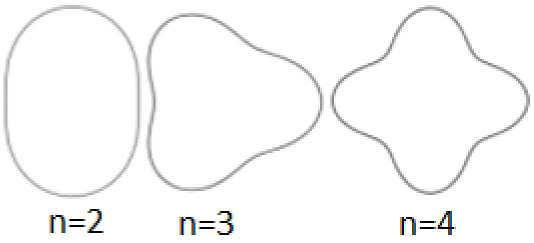
σ_x & σ_y → RMS widths of density distribution

- **Geometric fluctuations included**
- **Geometric quantities constrained by multiplicity density.**

Collective Flow is acoustic



Initial Geometry characterized by many shape harmonics (ε_n) → drive v_n



$$\frac{dN}{d\phi} \propto \left(1+2\sum_{n=1} v_n \cos\left[n\left(\phi-\Psi_n\right)\right]\right)$$

Acoustic viscous modulation of v_n

$$\delta T_{\mu\nu}(t,k) = \exp\left(-\frac{2}{3}\frac{\eta}{s}k^2\frac{t}{T}\right)\delta T_{\mu\nu}(0)$$

$$t \propto \bar{R}$$

$$k = n/\bar{R} \qquad R_{out}, R_{side}, R_{long} \propto \bar{R}$$

Staig & Shuryak Phys.Rev. C84(2011) 034908

$$\delta T_{\mu\nu}(n,t) = \exp\left(-\beta n^2\right)\delta T_{\mu\nu}(0), \quad \beta = \frac{2}{3}\frac{\eta}{s}\frac{1}{\bar{R}^2}\frac{t}{T}$$

Roy A. Lacey et al, Phys.Rev.Lett. 112 (2014) 8;

Scaling expectations:

$\eta/s \propto \beta', \beta''$

System size dependence

$$\ln\left(\frac{v_n}{\varepsilon_n}\right) \propto \frac{-\beta''}{\bar{R}}$$

v_n is related to v_2

$$\frac{\left(v_n(p_T)\right)^{1/n}}{\left(v_2(p_T)\right)^{1/2}} \sim \frac{\left(\varepsilon_n\right)^{1/n}}{\left(\varepsilon_2\right)^{1/2}} \cdot \exp\left(-\beta'(n-2)\right)$$

n^2 dependence

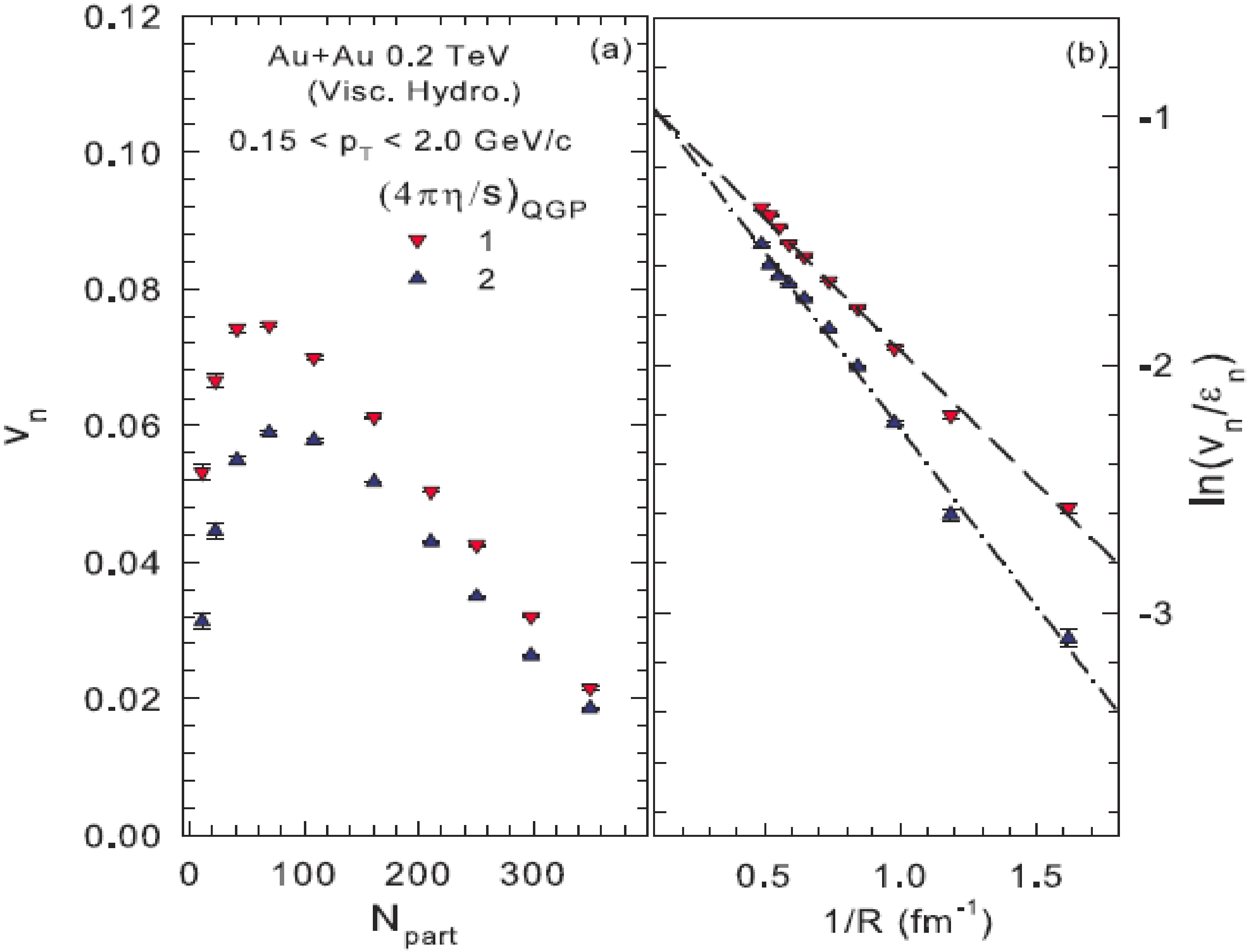
$$\left(\frac{v_n(p_T)}{\varepsilon_n}\right)^{1/n} \propto \exp\left(-\beta' n\right)$$

$1/\bar{R}$ scaling of anisotropic flow

H. Song, S. A. Bass, U. Heinz, T. Hirano, 273 and C. Shen, Phys.Rev. C83, 054910 (2011),

$$\ln\left(\frac{v_n}{\varepsilon_n}\right) \propto \frac{-\beta''}{\bar{R}}$$

- ✓ **Characteristic acoustic scaling validated for viscous hydrodynami**



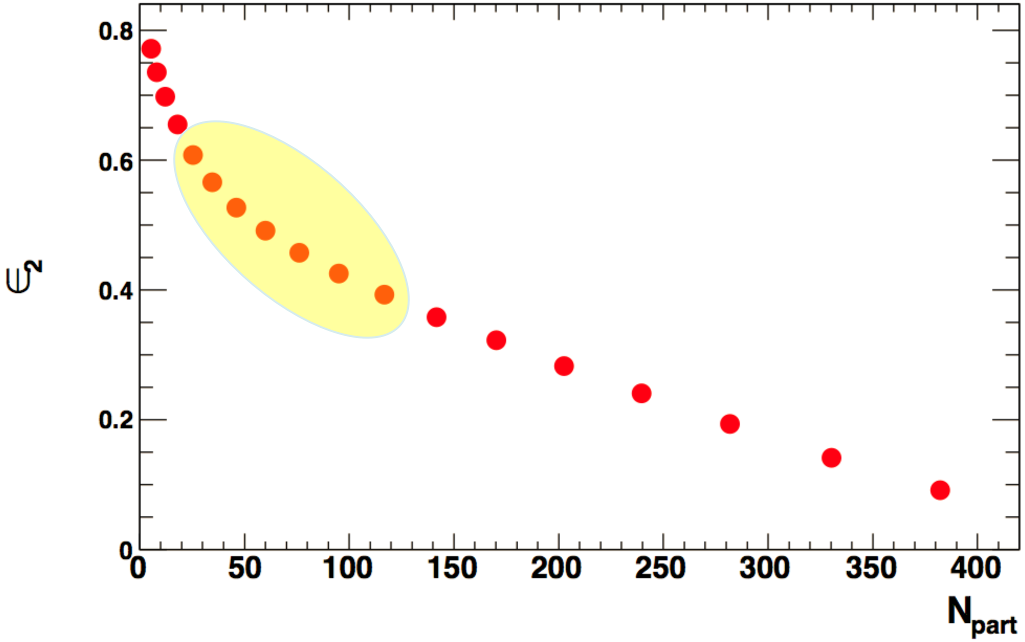
Phys.Rev.Lett. 112 (2014) 8

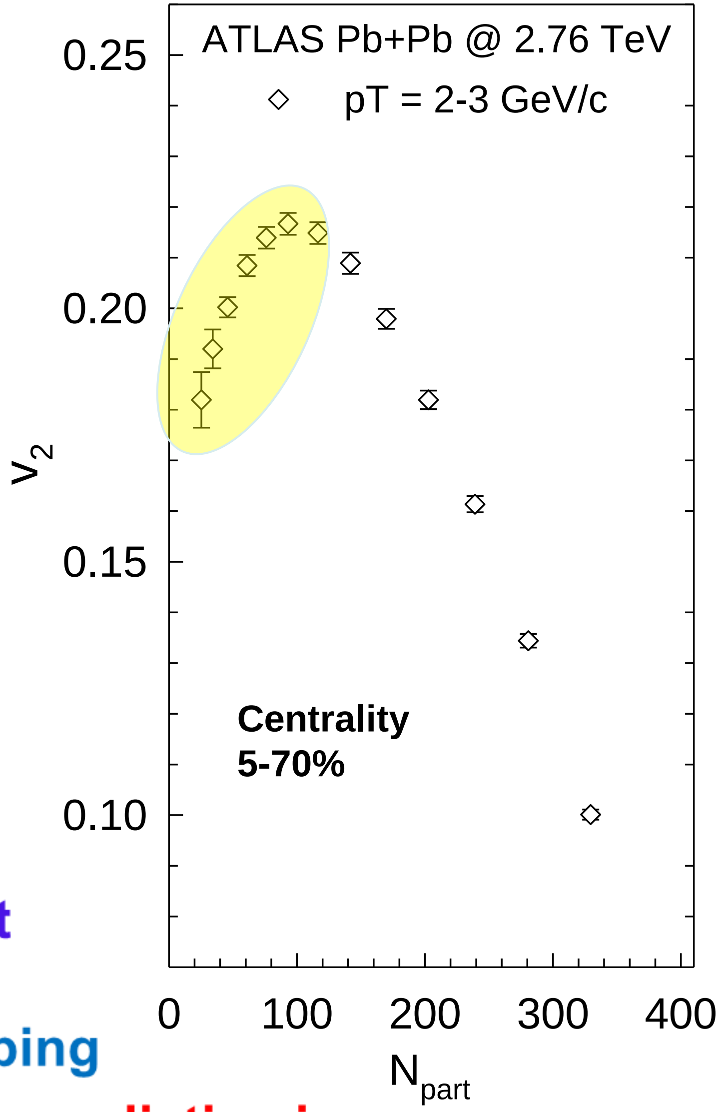
- ✓ ***β' shows clear sensitivity to η/s***
- ✓ **Viscous hydrodynamics can be used for calibration**

Scaling properties of flow

Acoustic Scaling – $\frac{1}{\bar{R}}$

$$\ln\left(\frac{v_n}{\varepsilon_n}\right) \propto \frac{-\beta''}{\bar{R}}$$





- ➢ **Eccentricity change <u>alone</u> is not sufficient**

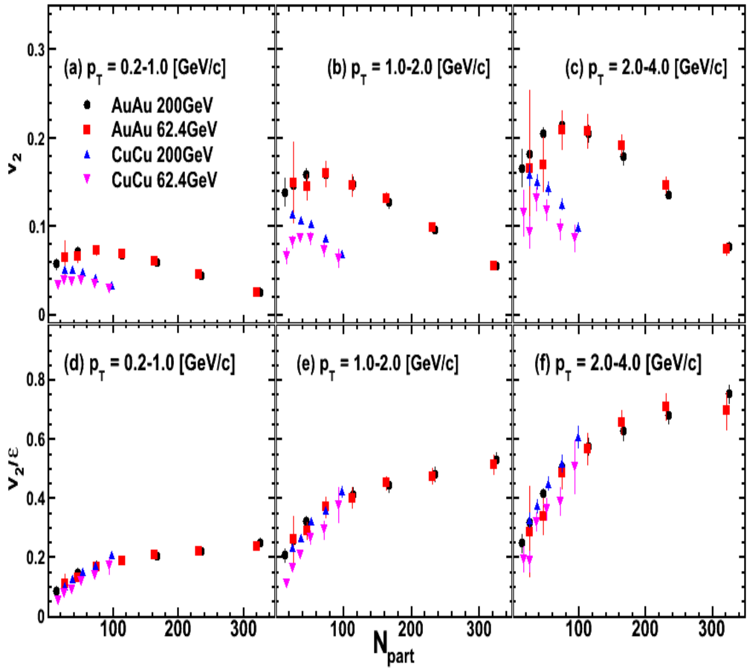
To account for the N_{part} dependence of v_n

Transverse size ($\bar{R}$) influences viscous damping

✓ **Characteristic $1/\bar{R}$ scaling prediction is non-trivial**

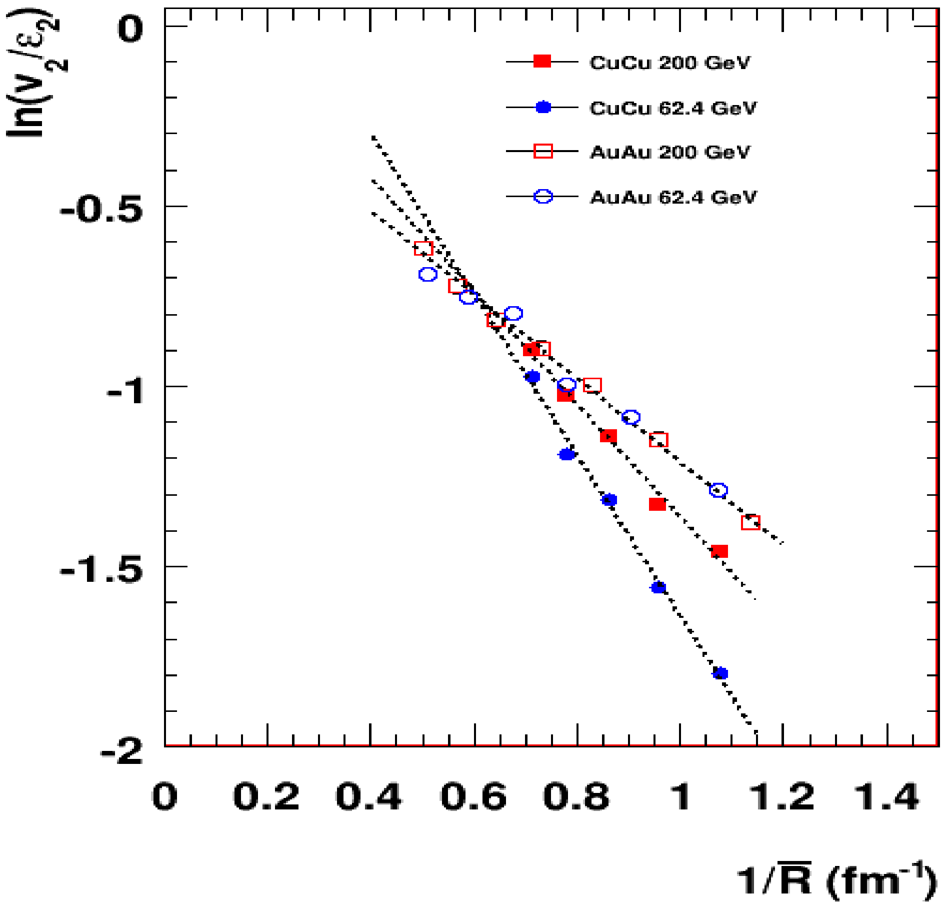
$1/\bar{R}$ scaling of anisotropic flow

PHENIX : arXiv:1412.1043



$$\ln\left(\frac{v_n}{\varepsilon_n}\right) \propto \frac{-\beta''}{\bar{R}}$$

$\ln(v_2/\varepsilon_2)$ vs $1/\bar{R}$, p_T=1-2 GeV/c, $[h^{\pm}]$

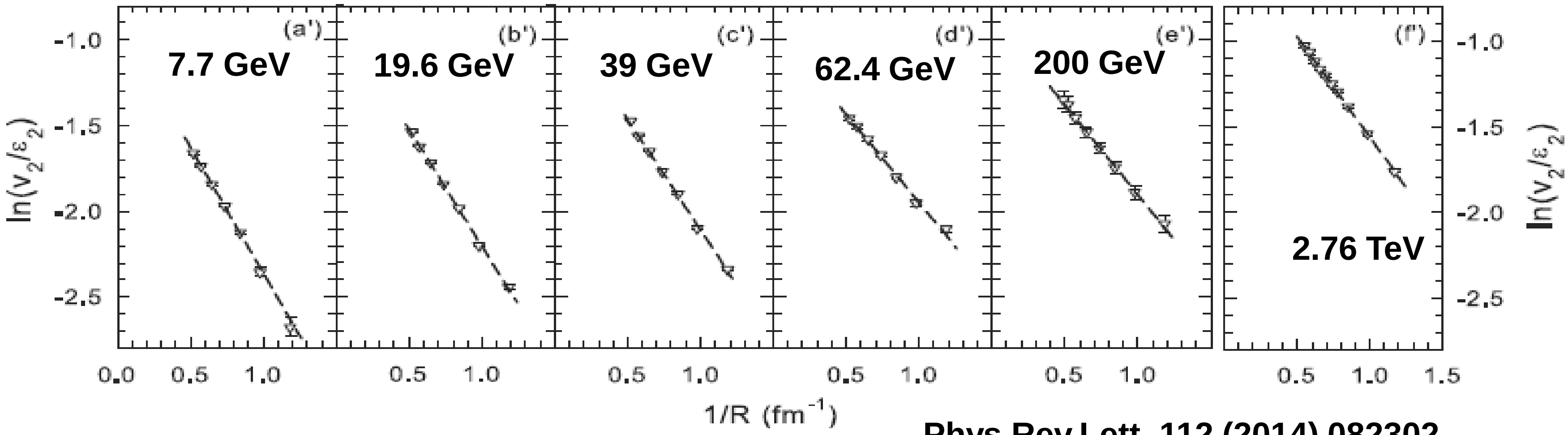


Slope parameter β″ is nearly the same for Au+Au at 62.4-200 GeV, but shows change from Au+Au to Cu+Cu at 200 GeV .

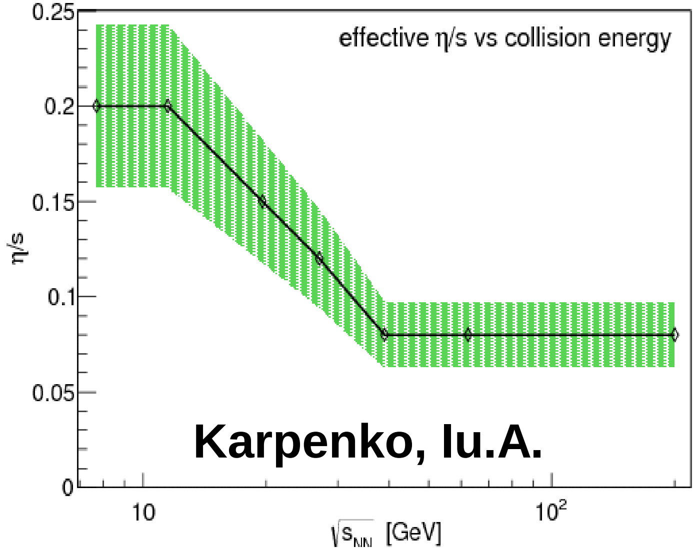
Can help to address the viscous damping in smaller systems / different beam energy dependence.

Acoustic Scaling – $\frac{1}{\bar{R}}$ *Scaling for the Beam Energy Scan*

$$\ln\left(\frac{v_n}{\varepsilon_n}\right) \propto \frac{-\beta''}{\bar{R}}$$

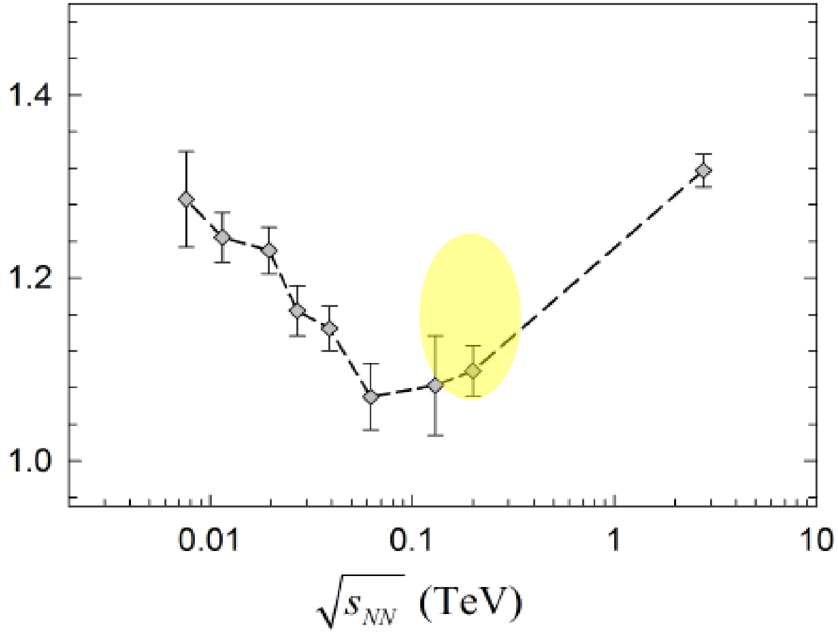


Phys.Rev.Lett. 112 (2014) 082302



Karpenko, Iu.A.

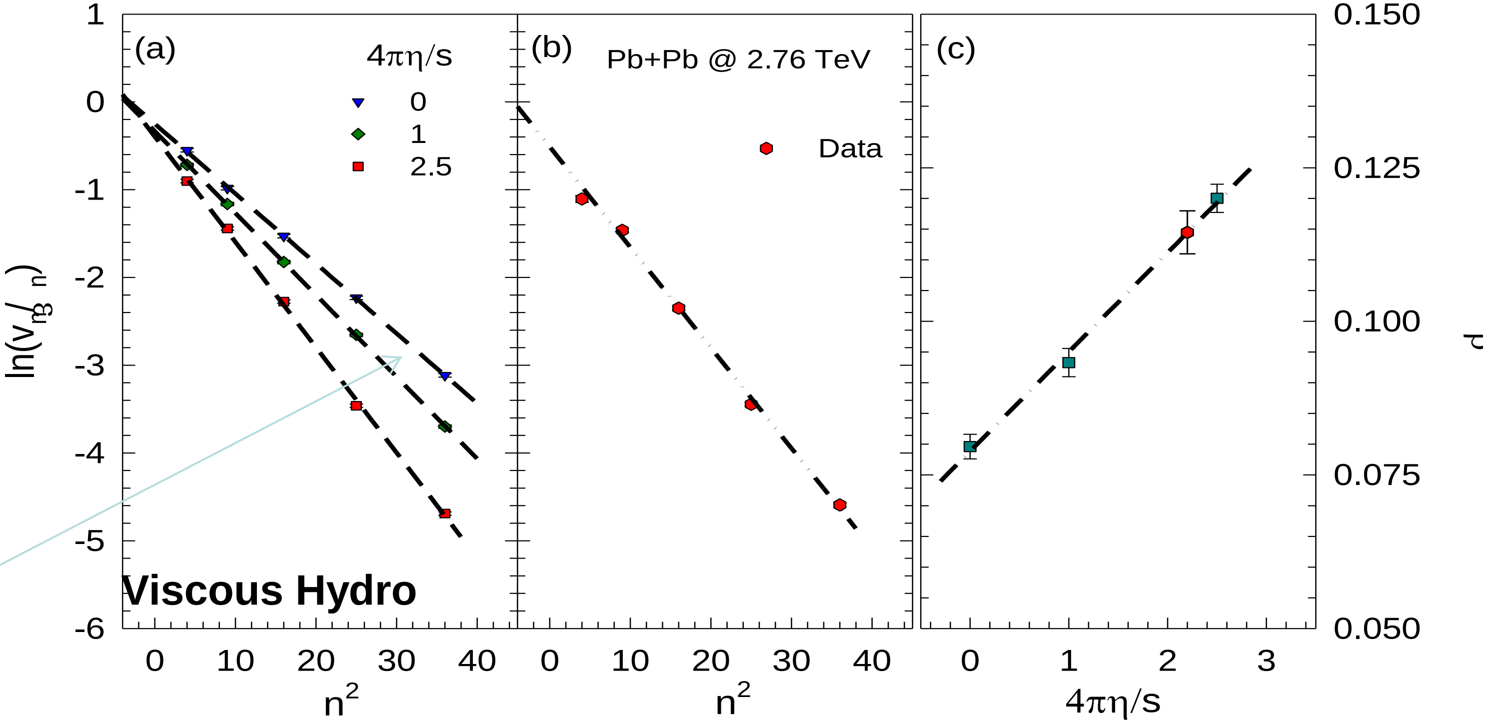
Phys.Rev. C91 (2015) 6, 064901



$$\frac{v_n(p_T)}{\varepsilon_n} \propto \cdot \exp\left(-\beta' n^2\right)$$

H. Song, S. A. Bass, U. Heinz, T. Hirano, 403 and C. Shen, Phys.Rev. C83, 054910 (2011),

arXiv:1301.0165



Slope sensitive to η/s

Characteristic n^2 viscous damping validated in viscous hydrodynamics and experimental data

To measure the centrality dependence of v2 and v3 During the beam energy scan is very important.

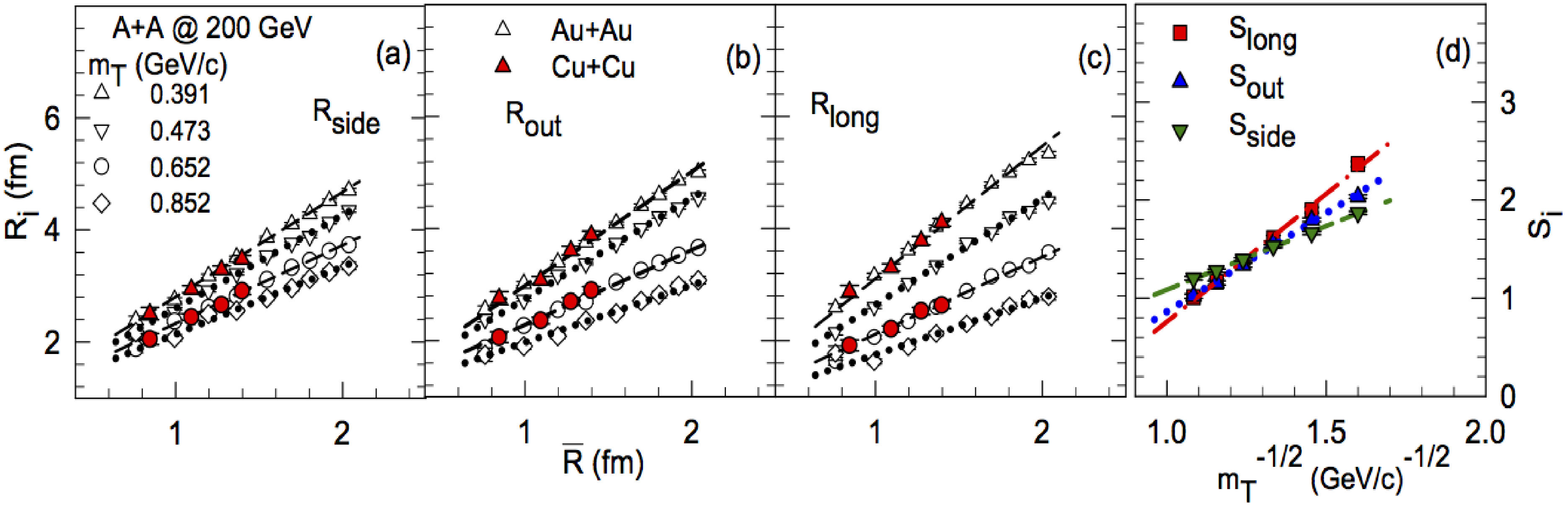
geometric scaling of HBT radii in HI collisions

$$t \propto \bar{R}$$

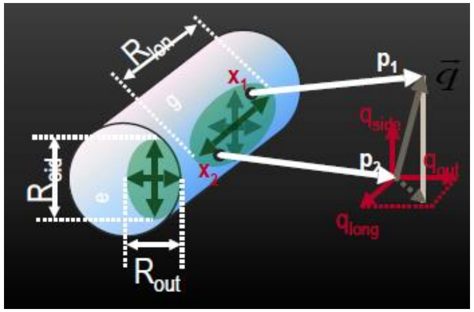
$$R_{out}, R_{side}, R_{long} \propto \bar{R}$$

arXiv: 1410.2559 [nucl-ex]

S_i are slopes from linear fits

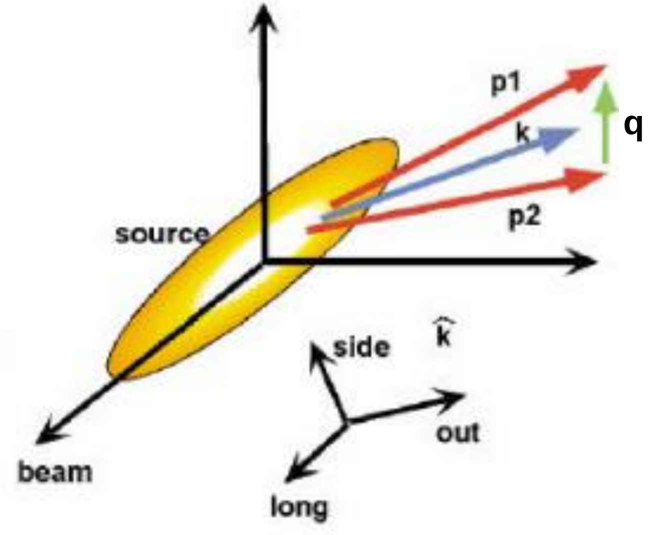


- **$\bar{R}$ and m_T scaling of the full RHIC data sets**
- **The centrality and m_T dependent data scale to a single curve for each radii.**
- **common expansion dynamics**



Expansion dynamics from HBT radii

HBT radii = initial size + expansion + position-momentum correlations



From the literature:

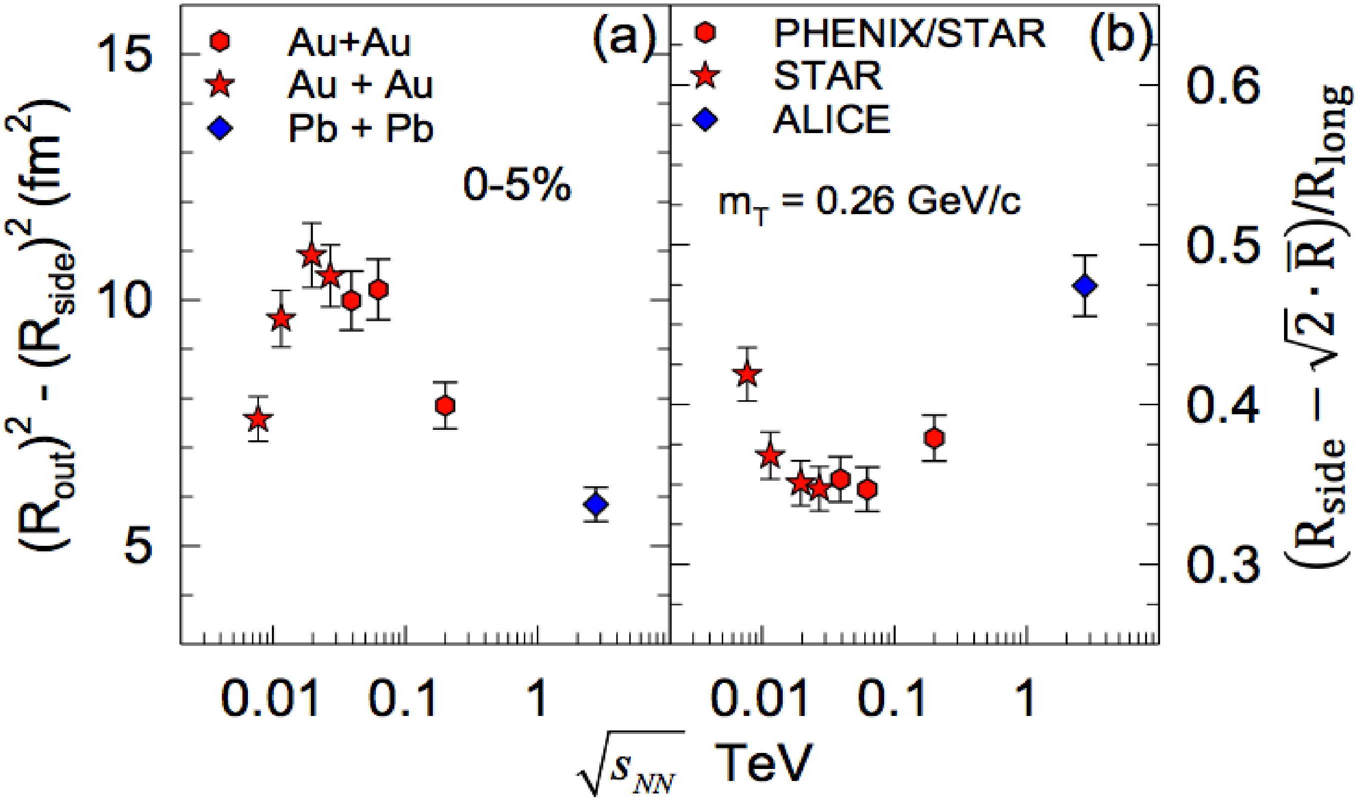
- ZPC 39, 69 (1988)
- PRL 74, 4400 (1995)
- PRL 75, 4003 (1995)
- NPA 608, 479 (1996)
- PRC 53, 918 (1996)

$R_{\mathrm{long}} \propto \tau$	**emission lifetime**
$(R_{\mathrm{side}} - \sqrt{2}\bar{R})$	**expansion radius for small m_T**
$(R^2_{\mathrm{out}} - R^2_{\mathrm{side}}) \propto \Delta\tau^2$	**emission duration**
$(R_{\mathrm{side}} - \sqrt{2}\bar{R})/R_{\mathrm{long}}$	**expansion rate**

for central collisions, the initial-state Gaussian radius is $R = \sqrt{2}\bar{R}$

$\sqrt{s_{NN}}$ dependence of interferometry signal

arXiv: 1410.2559 [nucl-ex]



$$\left(R_{out}^2 - R_{side}^2\right) \propto \Delta\tau^2$$

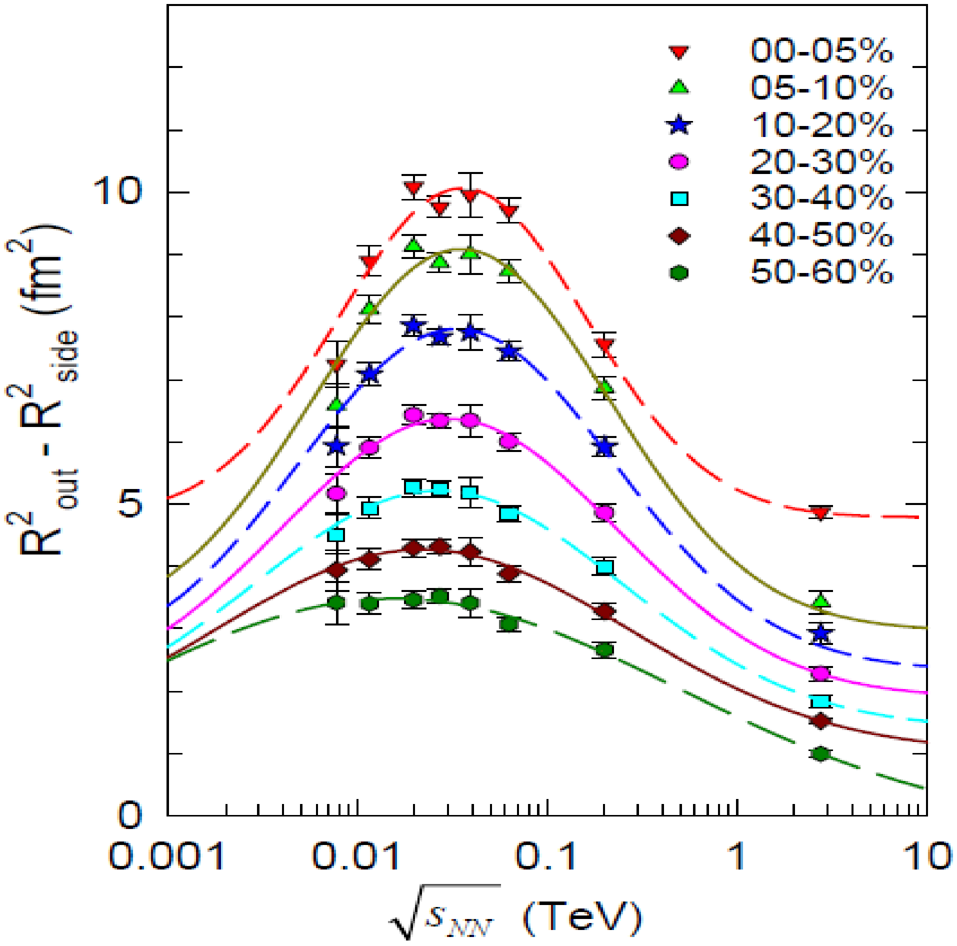
$$\left(R - R_i\right)/R_{long} \propto u$$

$$R_i = \sqrt{2}\bar{R}$$

Non-monotonic behavior with a maximum in emission duration $\Delta\tau$ and corresponding minimum in expansion rate in this beam energy range.

These characteristic non-monotonic patterns signal a suggestive change in the reaction dynamics

Size dependence of the HBT excitation functions



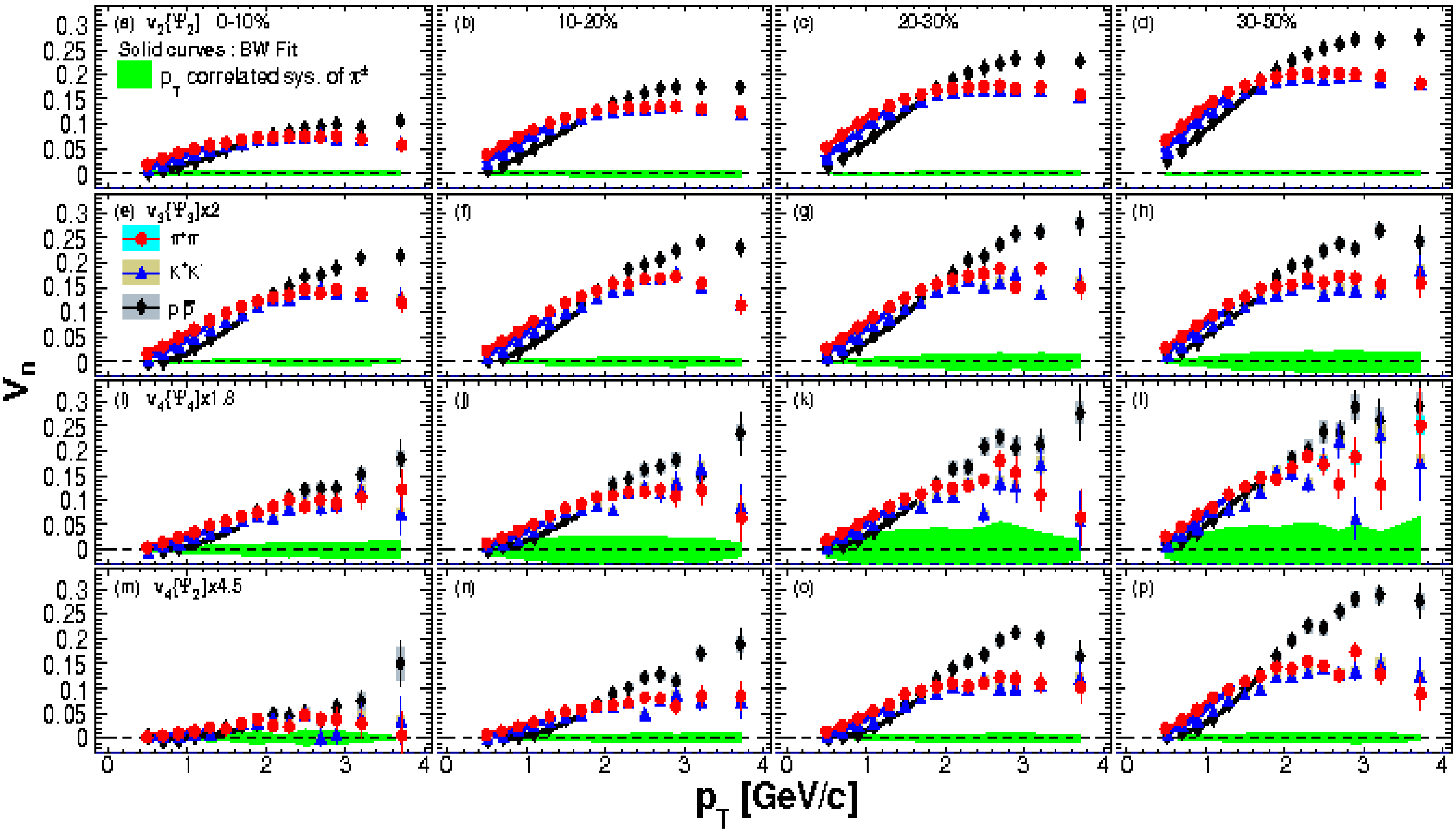
I. Max values decreases with decrease in system size
II. Peaks shift with decreasing system size
III. Widths increase with decreasing system size

These characteristic patterns signal the effects of finite-size

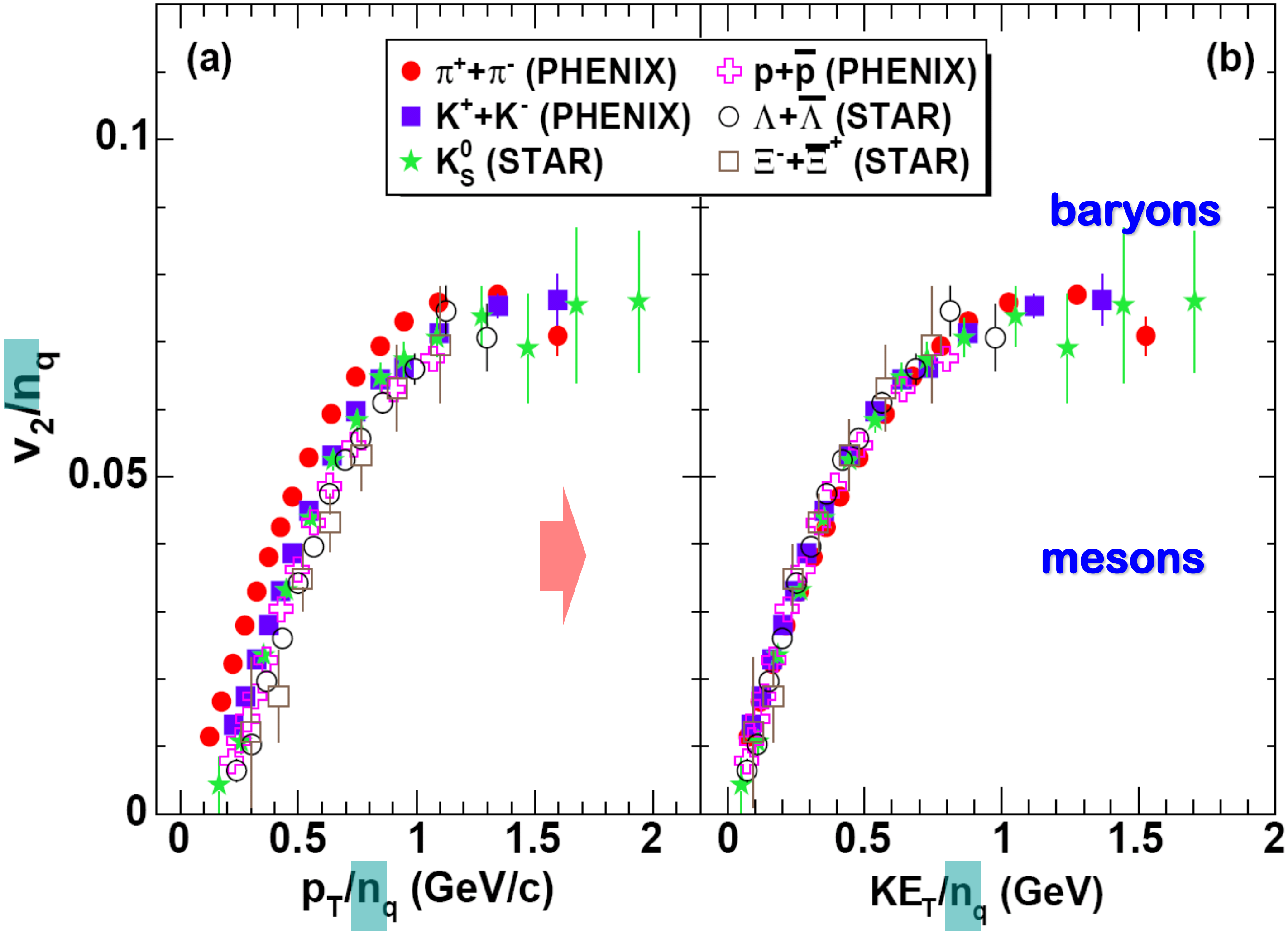
Indications for a Critical End Point in the Phase Diagram for Hot and Dense Nuclear Matter
Roy A. Lacey (SUNY, Stony Brook).
Published in Phys.Rev.Lett. 114 (2015) 14, 142301

v_2 , v_3 , v_4 of Identified charged hadrons Au+Au at 200 GeV

arXiv:1412.1038



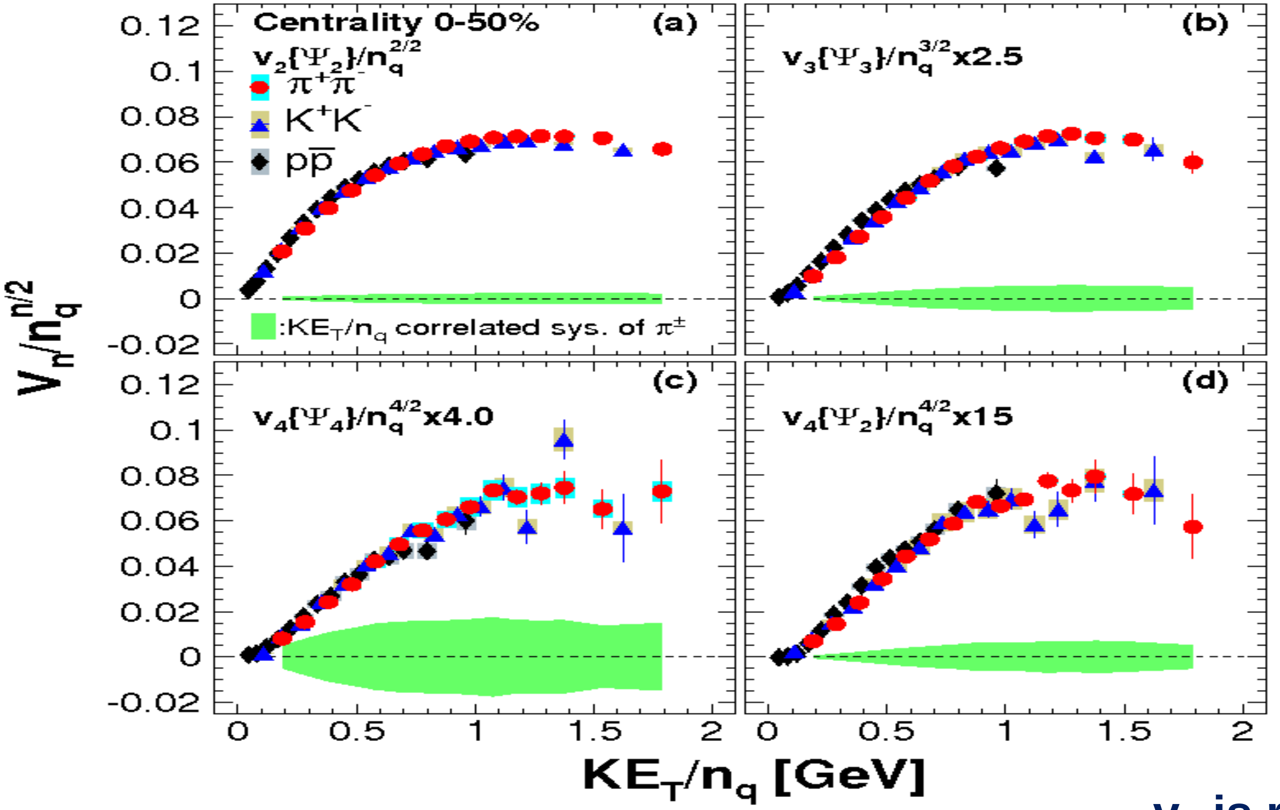
Quark number scaling and hadronization at RHIC



2006: Scaling Characteristics of Azimuthal Anisotropy at RHIC
Presented at Conference: C06-03-11.3
e-Print: nucl-ex/0604011

Scaling Properties of Vn Flow at 200 GeV

arXiv:1412.1038



v_n is related to v_2

$$v_{n,q}(KE_T) \sim v_{2,q}^{n/2} \quad \text{or} \quad \frac{v_n}{(n_q)^{n/2}}$$

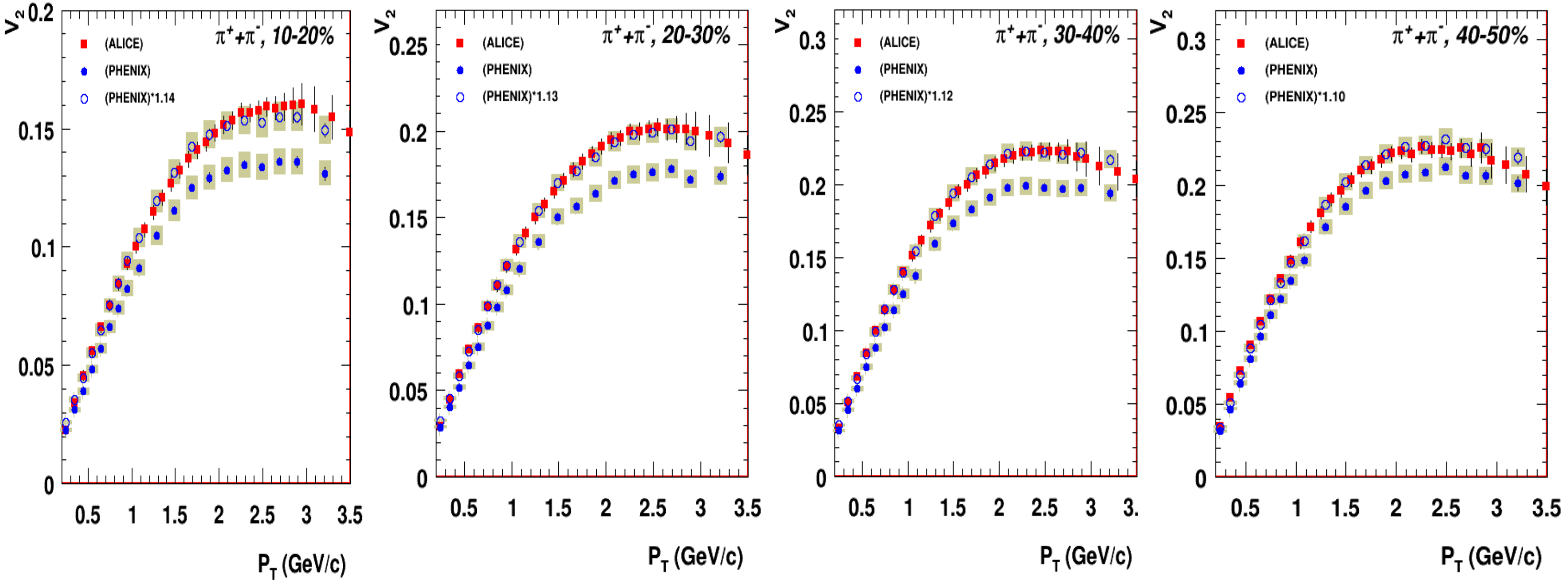
$$\frac{v_n(p_T)}{v_2(p_T)} = \frac{\varepsilon_n}{\varepsilon_2} \cdot \exp\left(-\beta(n^2-4)\right)$$

- NCQ-scaling holds well for v_2,v_3,v_4 below 1GeV in KE_T space, at 200GeV

Comparison with LHC ALICE Pb+Pb at 2.76 TeV : charged pions

ALICE: CERN-PH-EP-2014-104
e-Print: **arXiv:1405.4632**

PHENIX
arXiv:1412.1038 , **arXiv:1412.1043**



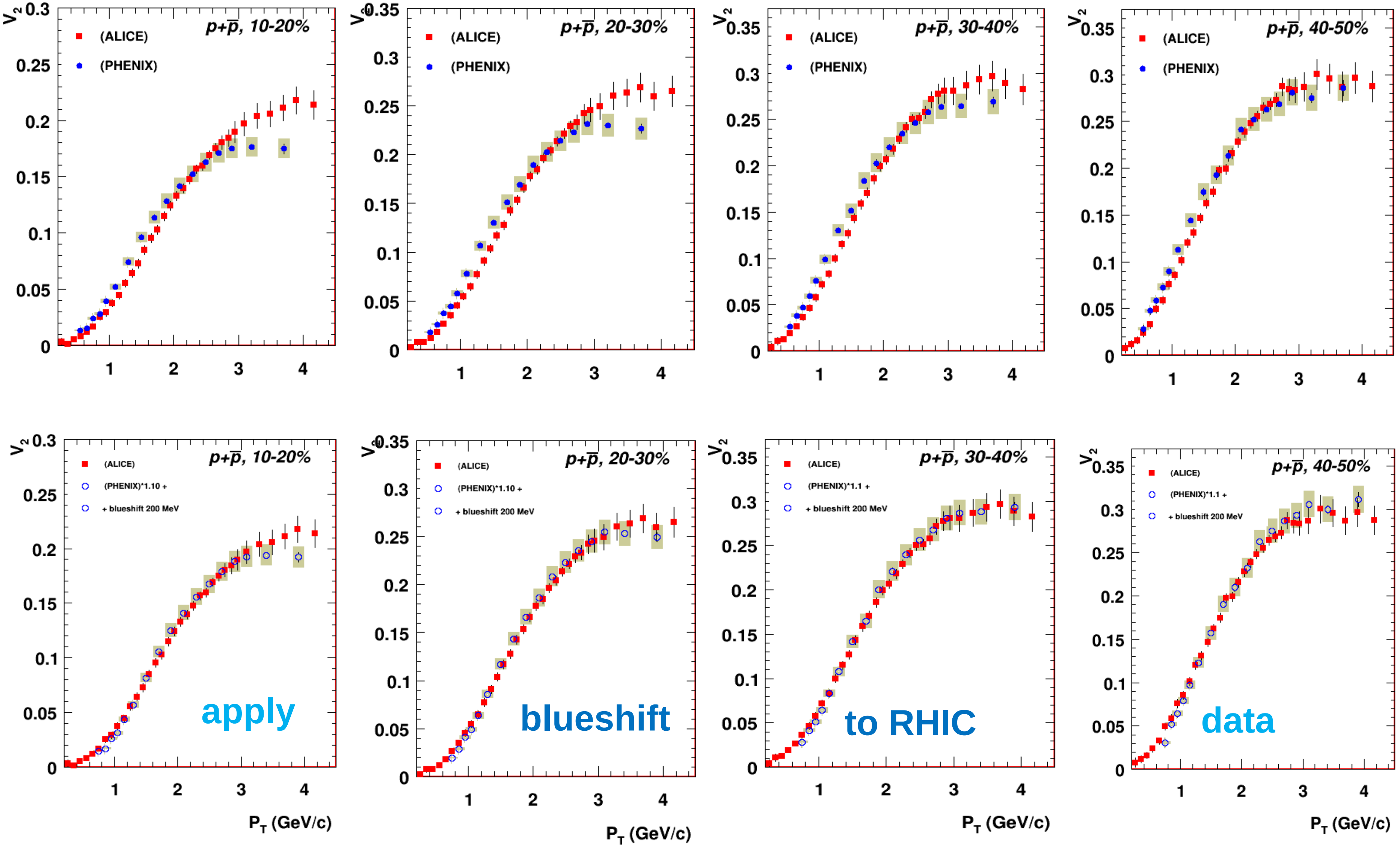
V2(pt) shape if very similar for charged pions between RHIC/LHC: 10-14% difference (pT = pT(thermal) + mcβ)

The difference in eccentricities between : ε2(PbPb at 2.76TeV) and ε2(Au+Au at 200 GeV) will increase the difference by 5-7%.

Comparison with LHC ALICE Pb+Pb at 2.76 TeV : (anti)protons

ALICE:: **arXiv:1405.4632**

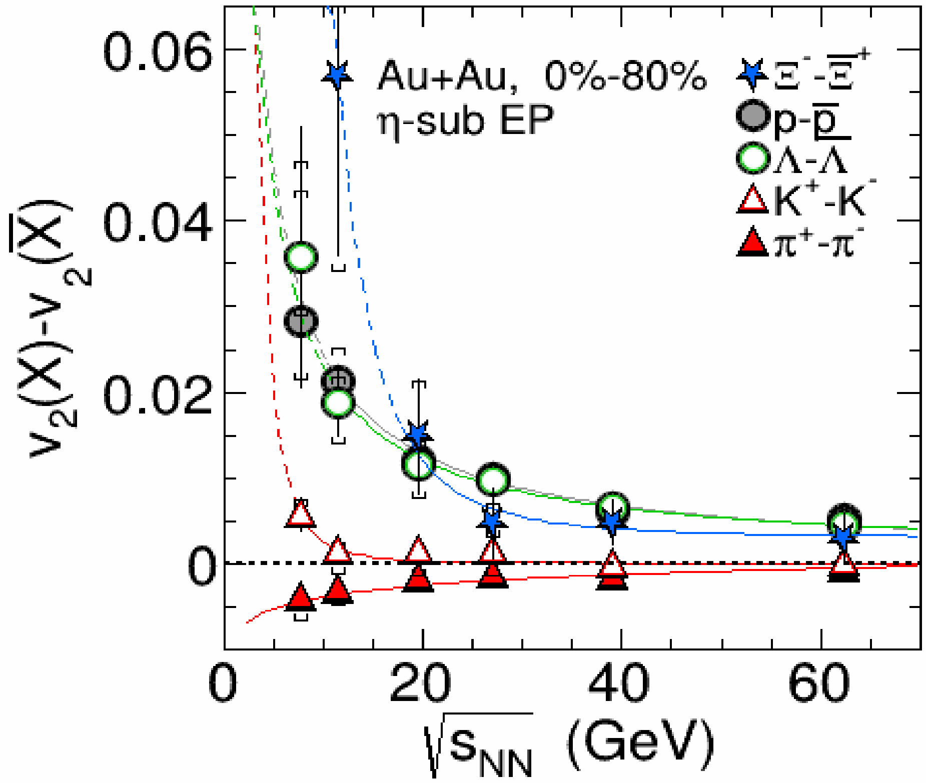
PHENIX **arXiv:1412.1038** , **arXiv:1412.1043**

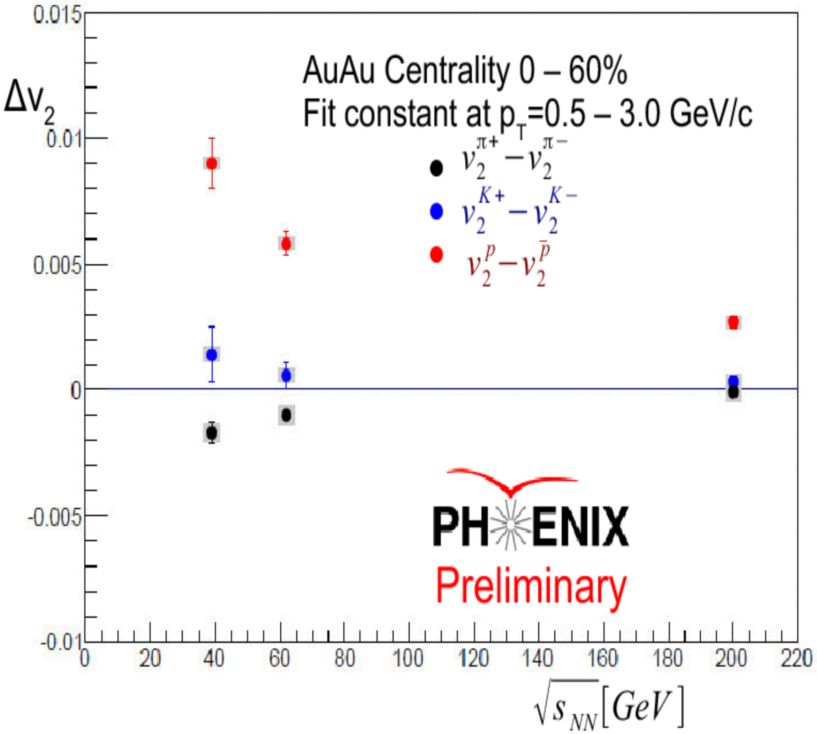


Δv_2 (particles – anti-particles) vs. $\sqrt{s_{NN}}$

STAR

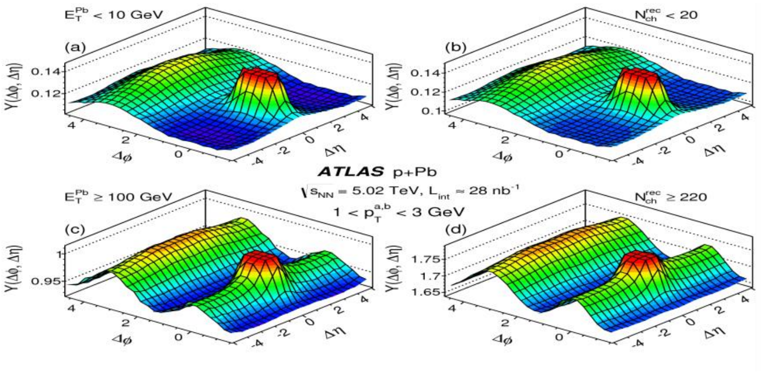
Phys. Rev. Lett. 110, 142301 (2013)



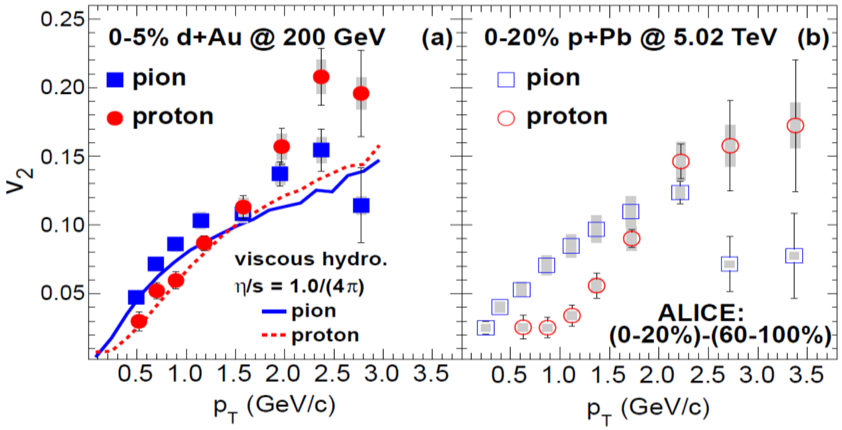


- **Hydro model: Hybrid model (UrQMD + hydro) with baryon stopping**
- **Nambu-Jona-Lasinio (NJL): Using vector mean-field potential, repulsive for quarks, attractive for anti-quarks**

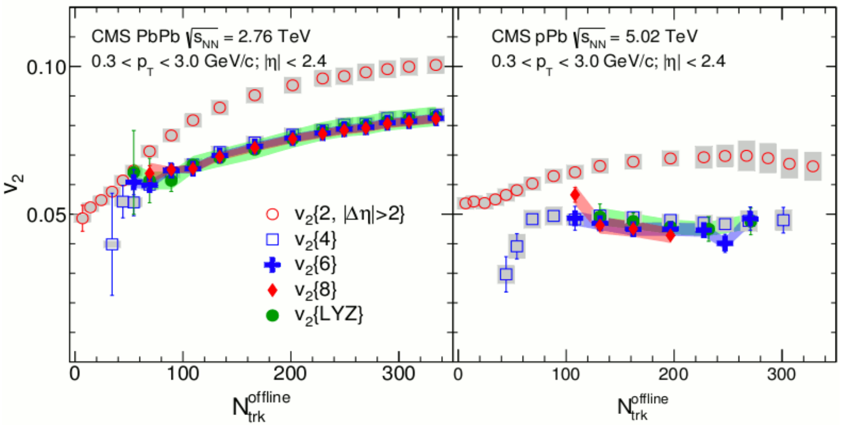
Collective Effects in Small Systems: LHC and RHIC: p+Pb , d+Au



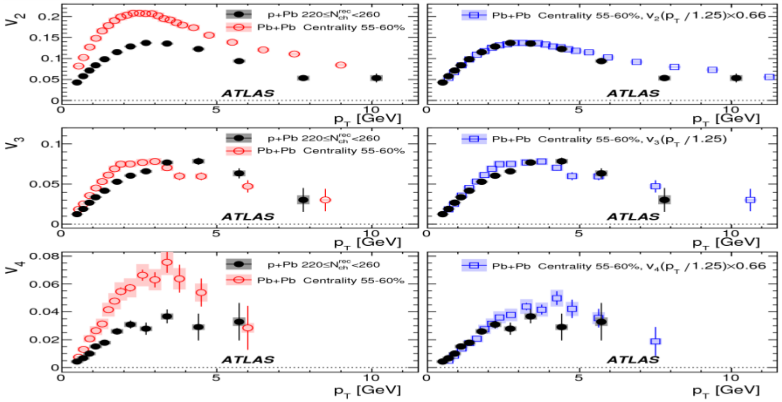
Long-range correlations: double ridge : CMS, ATLAS, ALICE, PHENIX,STAR



Mass ordering of PID v2 in p+Pb (ALICE,CMS) and d+Au (PHENIX)

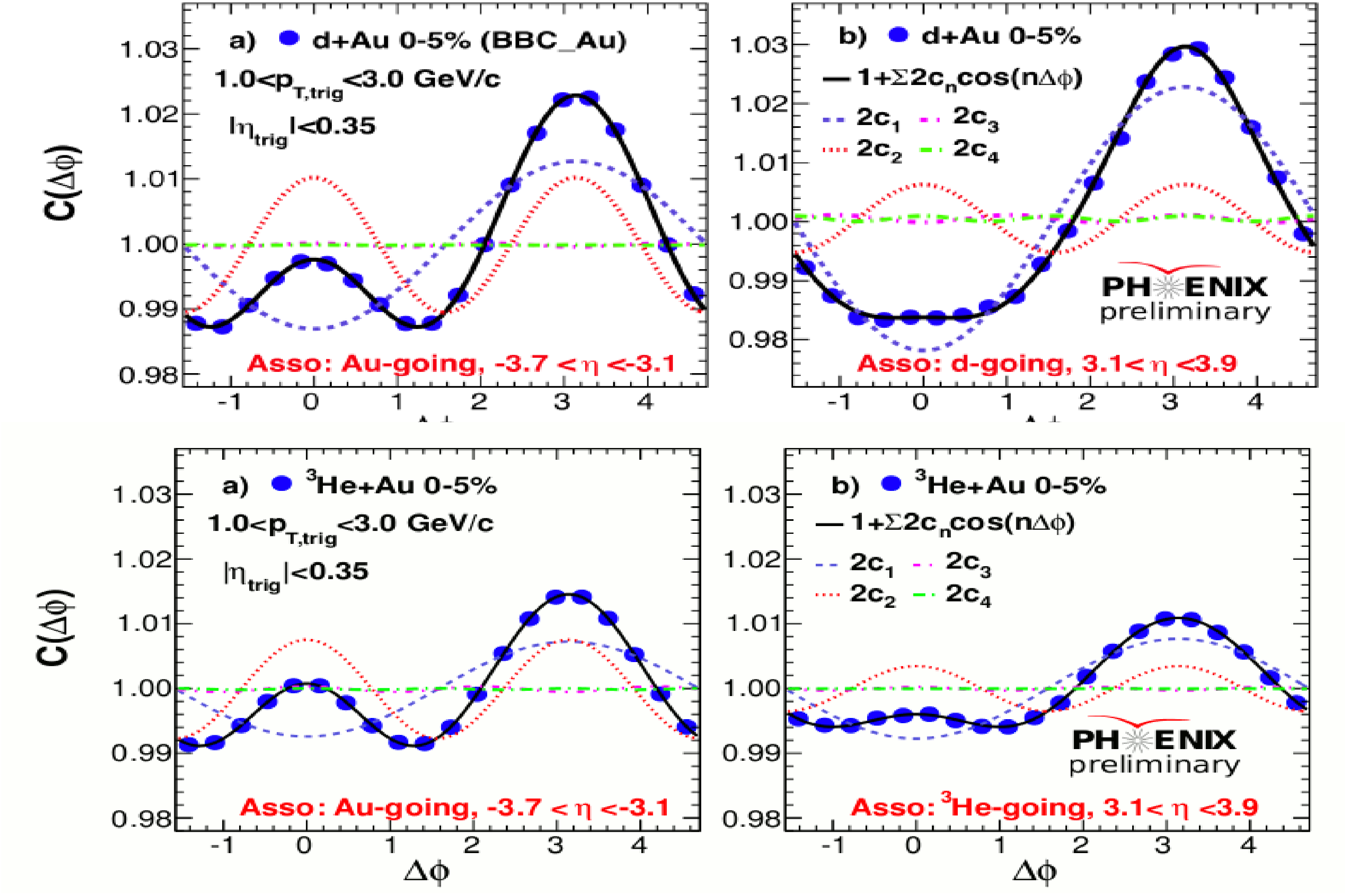


Multiparticle correlations: CMS, ATLAS, ALICE



Scaling relations: p+Pb vs Pb+Pb: CMS,ATLAS

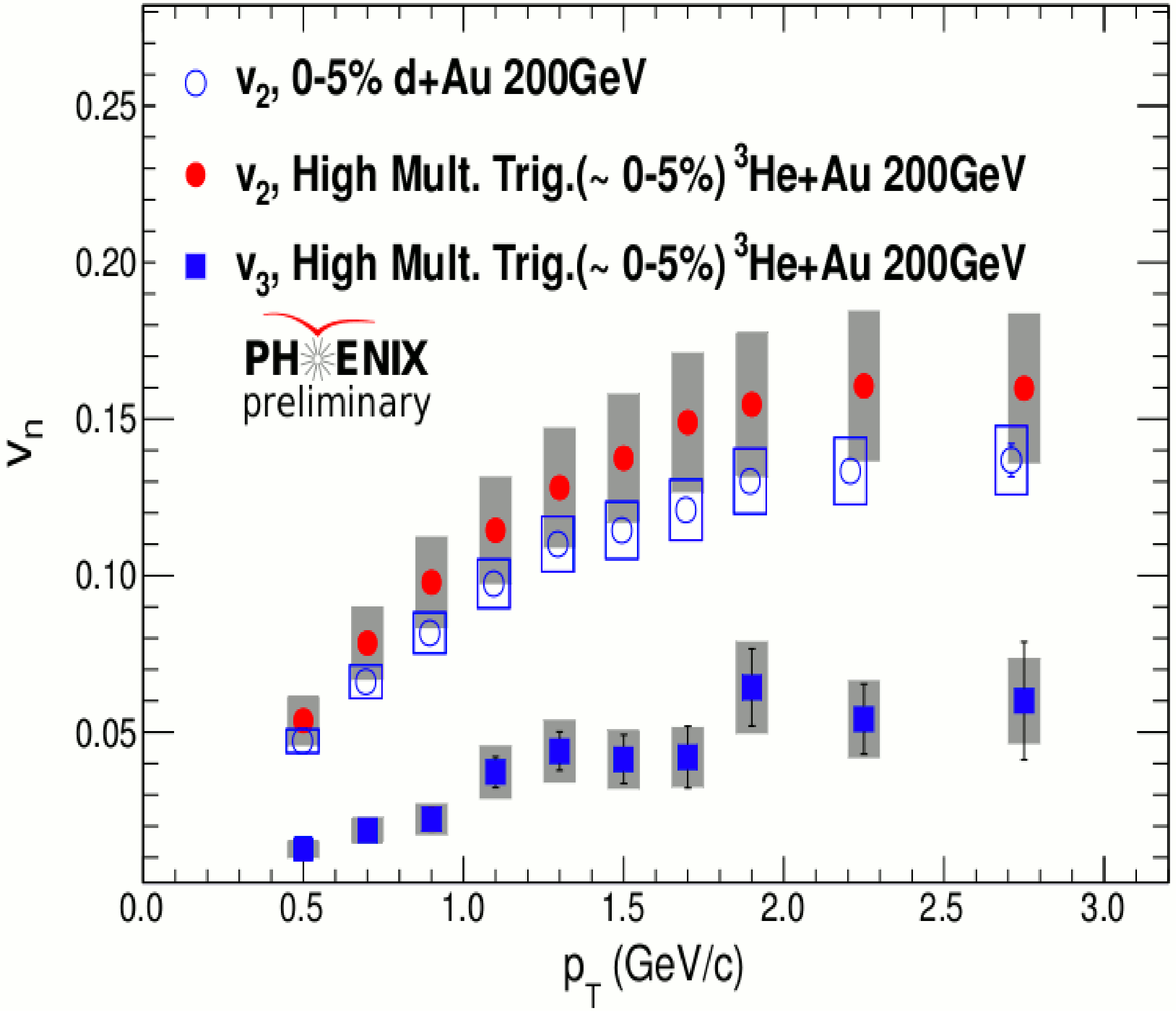
Long range correlation in d+Au/^{3}He+Au



Ridges are seen on both Au-going and ^{3}He-going sides

| Δη| > 2.75 : MPC – hadron correlations

The v_2 and v_3 in ^{3}He+Au



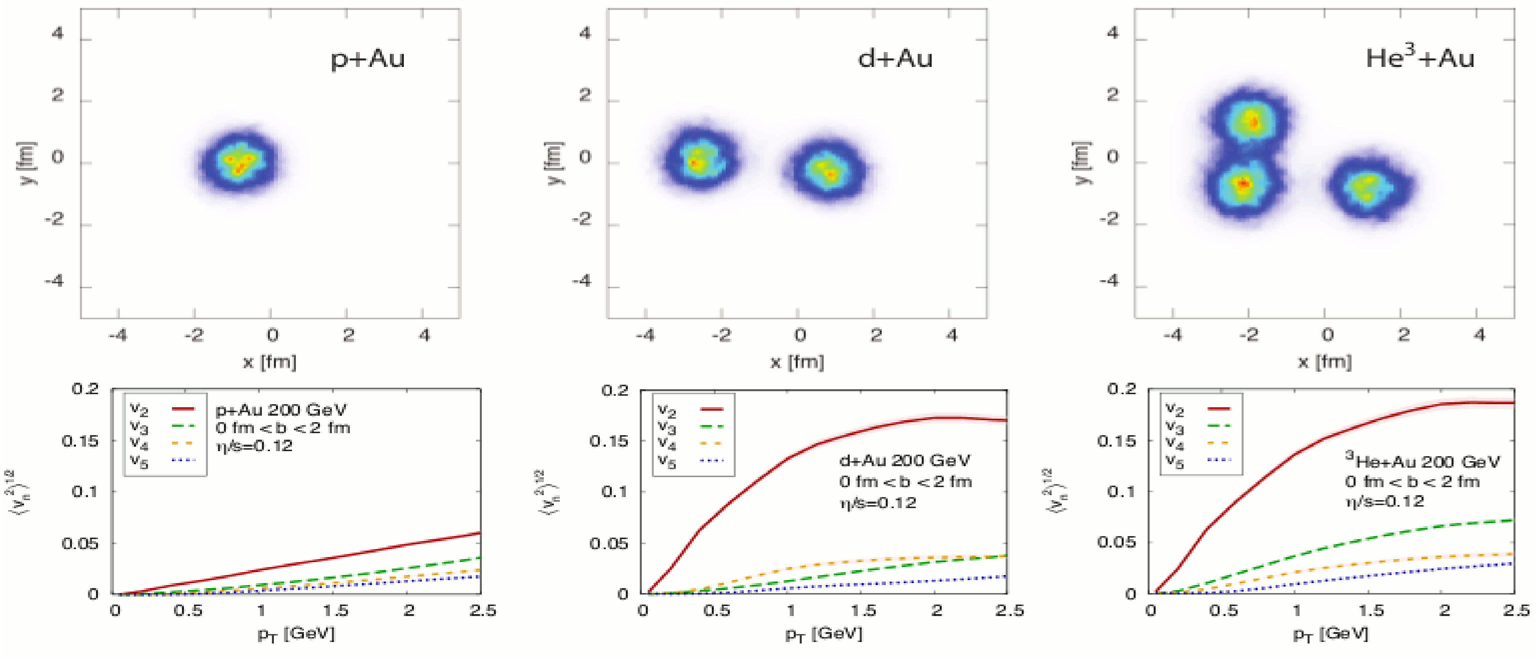
The v_2 of ^{3}He+Au is similar to that of d+Au

A clear v_3 signal is observed in 0-5% ^{3}He+Au collisions

PHENIX Plan to study more systems

| Δη| > 2.75 : Event plane method

PHENIX Plan to study more systems



Schenke 1407.7557

2013: d+Au at 200 GeV

2014: ^{3}He+Au (with high multiplicity trigger)

2015: p+p, p+Au, p+Al (with high multiplicity trigger)

2016: interested in beam energy scan for p+Au or d+Au collisions (20, 39 , 62, 200 GeV)

Summary

- **V_2 and V_3 studied in different colliding systems: Au+Au/Cu+Cu and Cu+Au:**
  - ➢ *Acoustic scaling of anisotropic flow*
  - ➢ *Viscous damping effects appear to be larger for smaller systems*
  - ➢ *Beam energy dependence of η/s*
  - ➢ *STAR/PHENIX differences – need to be understood*
- **The v_n of identified charged hadrons presented as a function of pT and centrality**
  - ➢ Mass ordering for all harmonics at all centralities studied
  - ➢ Measurements can be scaled by generalized quark number scaling
  - ➢ *Comparison with LHC and BES results*
- **The ridge is observed in d+Au and ^{3}He+Au.**
  - ➢ Similar magnitudes observed for v2
  - ➢ v_3 signal observed for ^{3}He+Au
- **From HBT radii in symmetric HI collisions:**

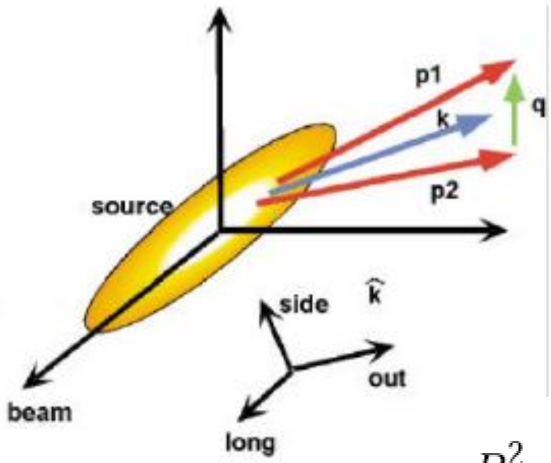
➢ *Nonmonotonic behavior in this beam energy range of emission duration and expansion rate*

➢ *change in expansion dynamics in this energy range*

Backup Slides

HBT Observables

Chapman, Scotto, and Heinz



$$R_l^2 = \tau_0^2 \frac{T}{m_\perp}\left[1 + \left(\frac{1}{2} + \frac{1}{1 + \frac{m_\perp}{T} v^2}\right)\frac{T}{m_\perp}\right]$$

$$R_{long} \propto \tau$$

$$R_s^2 = \frac{R^2}{1 + (m_\perp / T) v^2}$$

$$R_o^2 = \frac{R^2}{1 + (m_\perp / T) v^2} + \frac{1}{2}\left(\frac{T}{m_\perp}\right)^2 \beta_\perp^2 \tau_0^2$$

$$\left(R_{out}^2 - R_{side}^2\right) \propto \Delta\tau$$

proxy for the sound speed c_s

$$\left(R - R_i\right) / R_{long} \propto u$$

$$R_i = \sqrt{2}\,\bar{R}$$

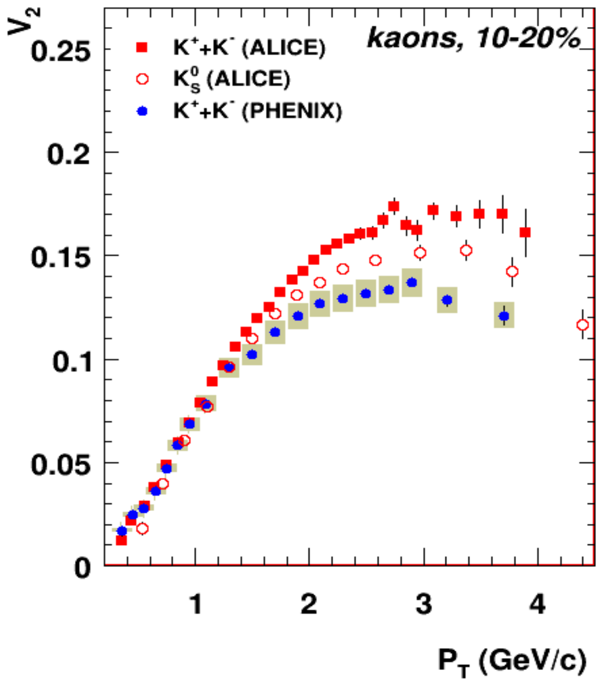
estimate for initial size in central events

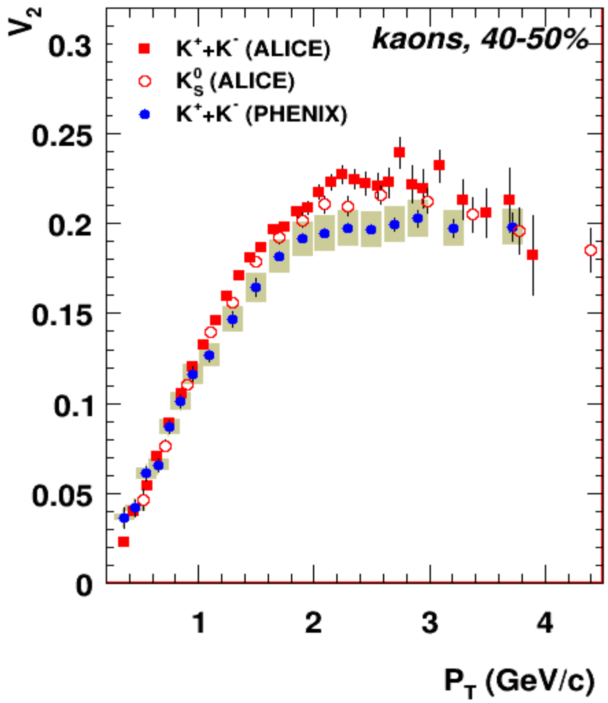
Study HBT observables as a function of $\sqrt{s_{NN}}$

Comparison with LHC ALICE Pb+Pb at 2.76 TeV : kaons

ALICE: CERN-PH-EP-2014-104
e-Print: arXiv:1405.4632

PHENIX
arXiv:1412.1038 . arXiv:1412.1043

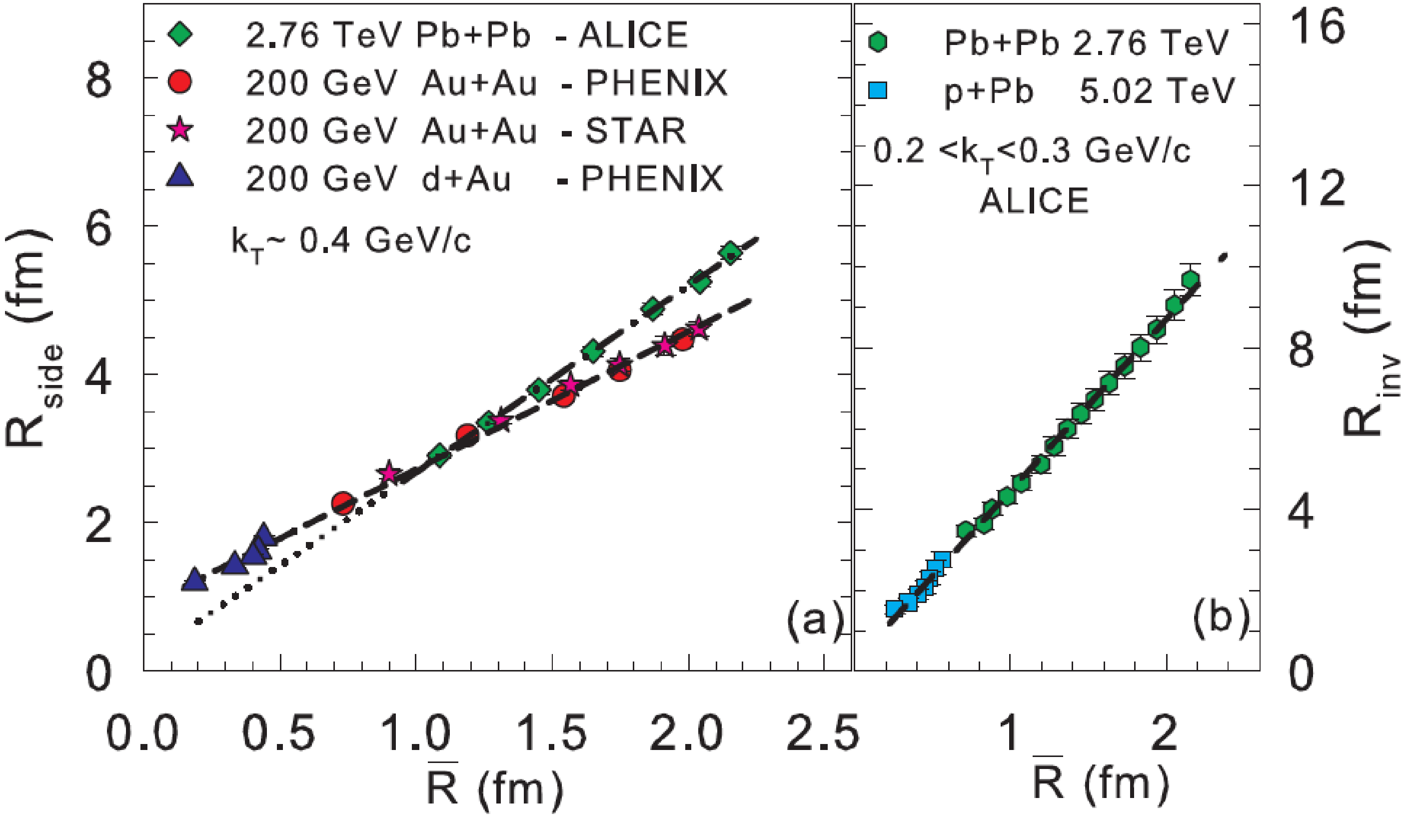




Difference in kaons between RHIC and LHC looks complicated, especially the difference between charged and neutral kaons at LHC.

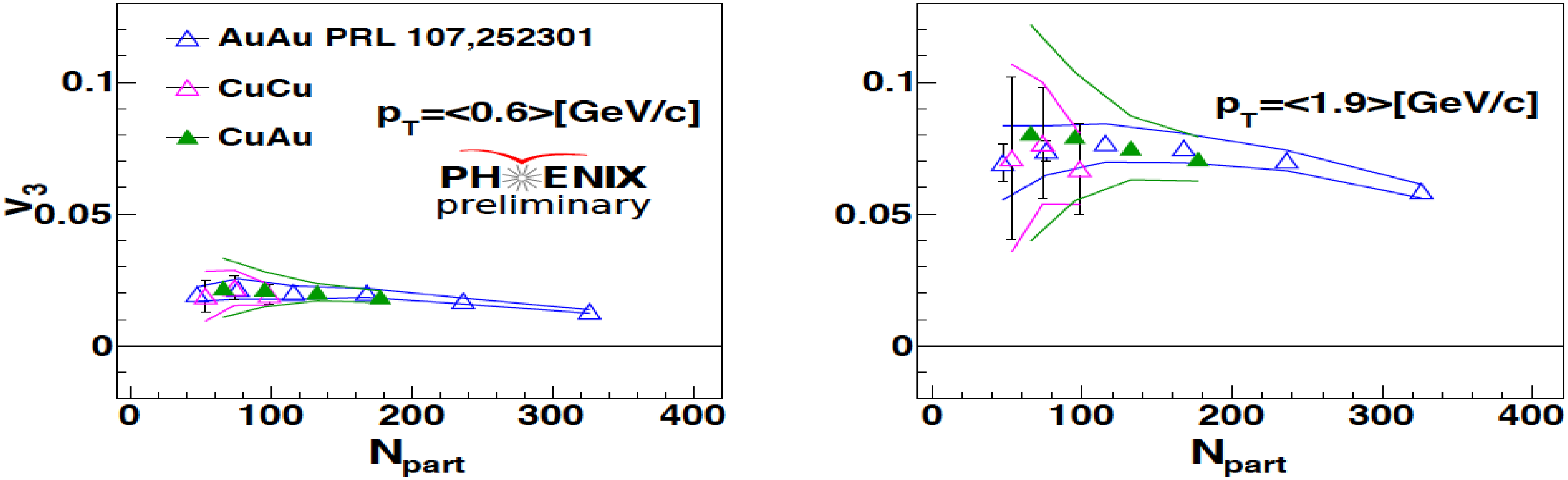
Geometric scaling of HBT radii

arXiv:1404.5291 [nucl-ex]



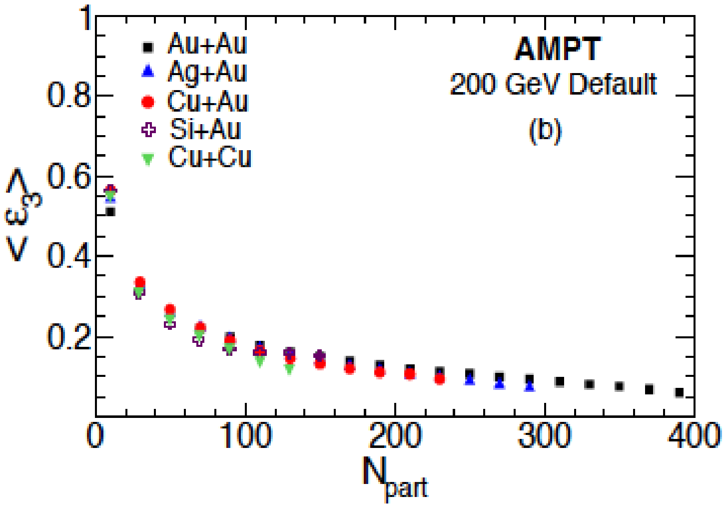
- *HBT radii scale with initial transverse size for both p(d)+A and A+A collisions*
- *larger slope corresponds to larger expansion rate for LHC data*
- *final-state rescattering effects are important in p(d)+A collisions also*

v_3 in 200 GeV Cu+Au vs Cu+Cu/Au+Au



The observed system size independence of v3
Is expected from the similar values of ε3

$$\frac{v_n(p_T)}{\varepsilon_n} = \alpha \cdot \exp\left(-\beta' n^2\right)$$

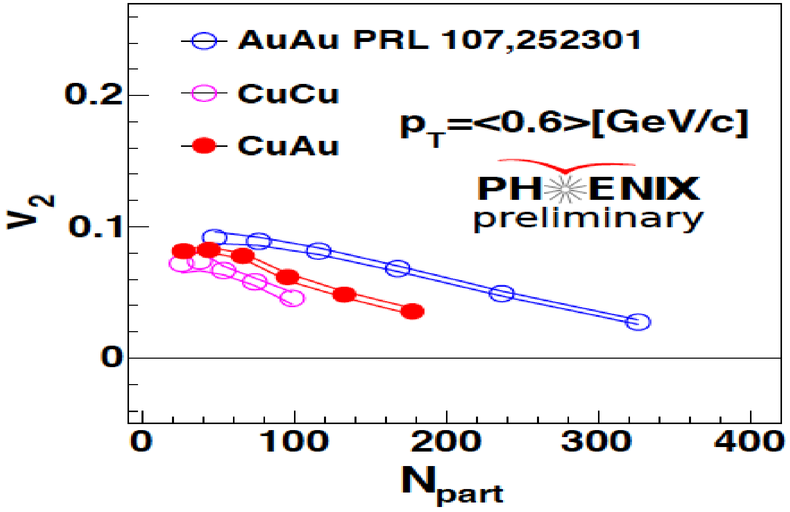


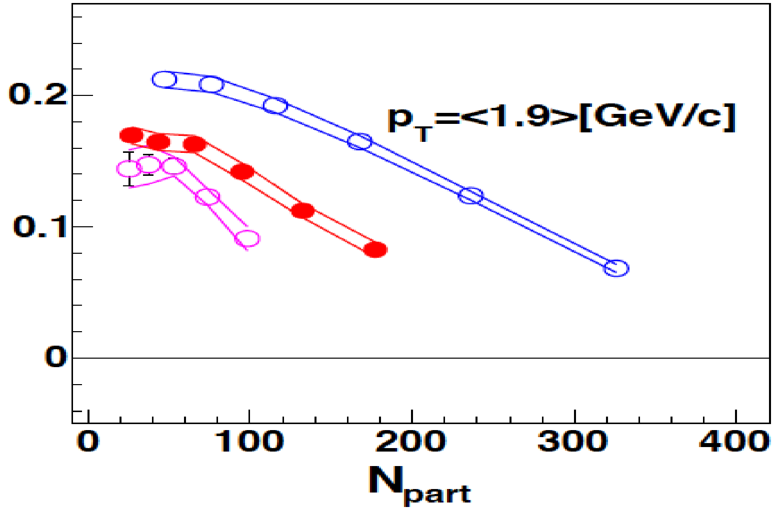
Phys.Rev. C84 (2011) 067901

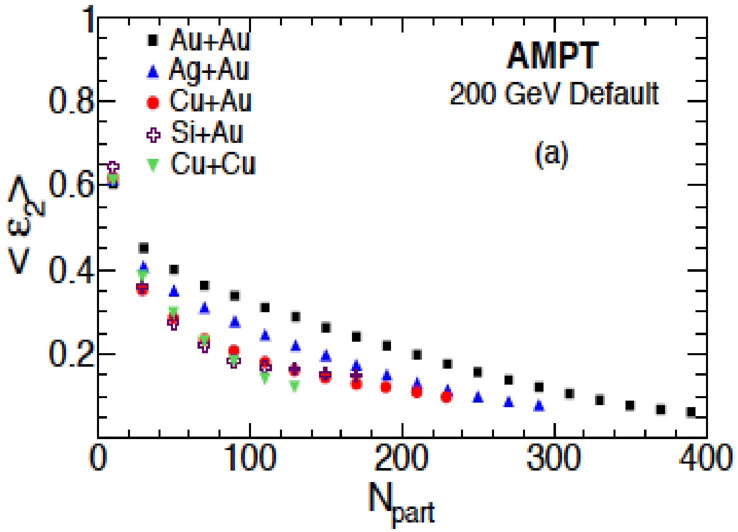
Simultaneus measurements of

v2 and v3 → Crucial constraint for η/s

v_2, in 200 GeV Cu+Au vs Cu+Cu/Au+Au







Phys.Rev. C84 (2011) 067901

The observed system size dependence of v2: AuAu>Cu+Au>CuCu originate from the differences in initial ε2

The general features of the collective flow could, in principle, be expressed in terms of scale-invariant quantities. In this way the particular differences arising from the different initial conditions, masses, energies, etc. , can be separated from the general fluid-dynamical features. Theoretical fluid-dynamical calculations predicted the collective flow long ago. " ' If perfect fluid dynamics is applicable under the conditions discussed in Ref. 10, then a scale-invariant representation of the data would eliminate the differences among the results. Deviations from such an ideal scaling signal physical processes which lead to a not-scale-invariant flow, like special properties of the equation of state (EOS), potential energy, or phase transitions, dissipation, relativistic effects, etc.

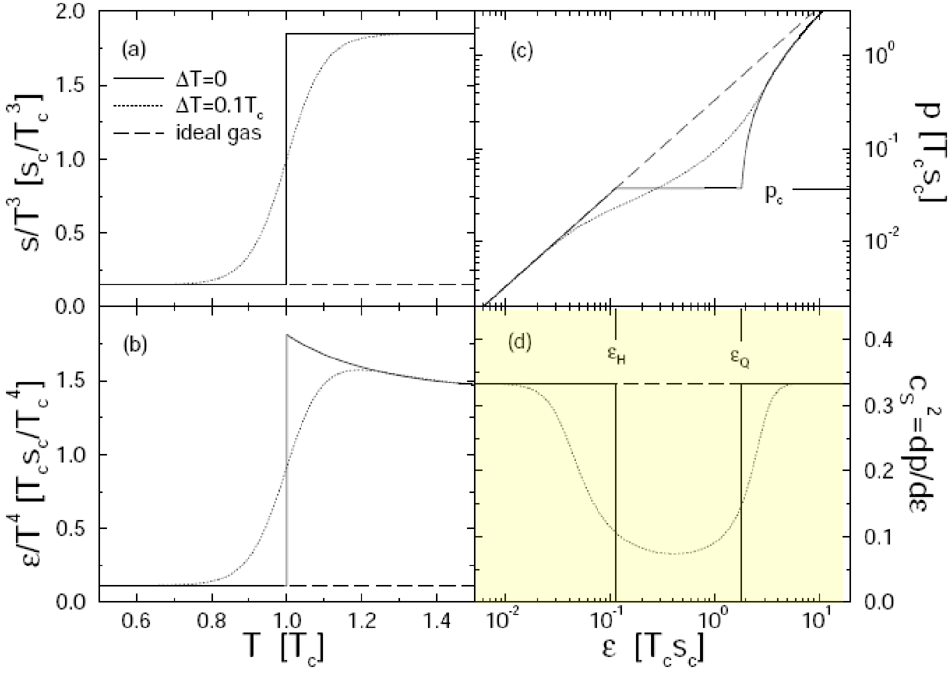
Collective flow in heavy-ion collisions W. Reisdorf, H.G. Ritter (Darmstadt, GSI & LBL, Berkeley). Dec 1997. 47 pp. Published in Ann.Rev.Nucl.Part.Sci. 47 (1997) 663-709 There is interest in using observables that are both coalescence- (27) and scale-invariant. Coalescence-invariant observables allow comparison with theories that are limited to making predictions for single-particle observables. Under certain conditions (2 the evolution in nonviscous hydrodynamics does not depend on the size of the system nor on the incident energy, if distances (such as impact parameters) are rescaled (reduced) in terms of a typical size parameter, such as the nuclear radius. Velocities, momenta and energies are rescaled in terms of the beam velocities, momenta or energies. Although the scaling conditions appear to be very restrictive, it is still useful to consider flow observables that are scale-invariant and thereby try to remove trivial consequences from size and incident velocity variations.

Possible signals

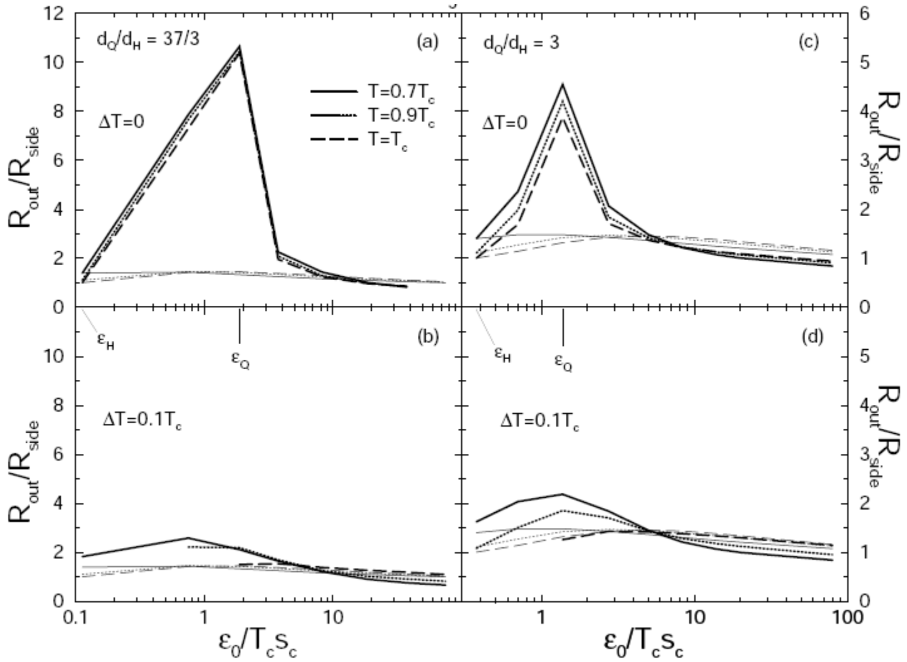
Collapse of directed flow

H. Stoecker, NPA 750, 121 (2005)

Dirk Rischke and Miklos Gyulassy
Nucl.Phys.A608:479-512,1996



Dirk Rischke and Miklos Gyulassy
Nucl.Phys.A608:479-512,1996



In the vicinity of a phase transition or the CEP, the sound speed is expected to soften considerably.

In the vicinity of a phase transition or the CEP anomalies in the space-time dynamics can enhance the time-like component of emissions.

v_1 and HBT measurements are invaluable probes

Ye Olde HBT formulae

- Formerly used to understand dynamics

  before era of multi-stage models, assumptions too restrictive

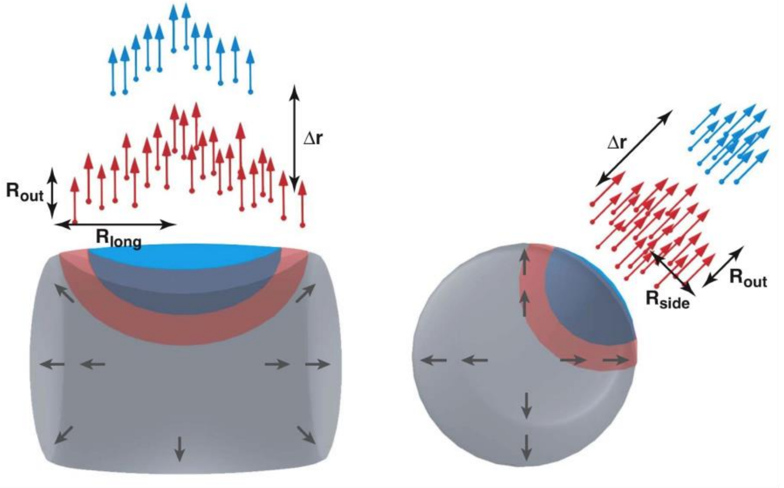
Chapman, Scotto, Heinz, PRL.74.4400 (95)

$$R_{side}^2 = \frac{R_{geo}^2}{1 + \frac{m_T}{T} b_T^2}$$

$$R_{out}^2 = \frac{R_{geo}^2}{1 + \frac{m_T}{T} b_T^2} + b_T^2 (\Delta\tau)^2$$

$$R_{long}^2 \approx \tau^2 \frac{T}{m_T} \frac{K_2}{K_1}$$

Makhlin, Sinyukov, ZPC.39.69 (88)



$$R_i = a + \frac{b}{\sqrt{m_T}}$$

empirical fit just as effective

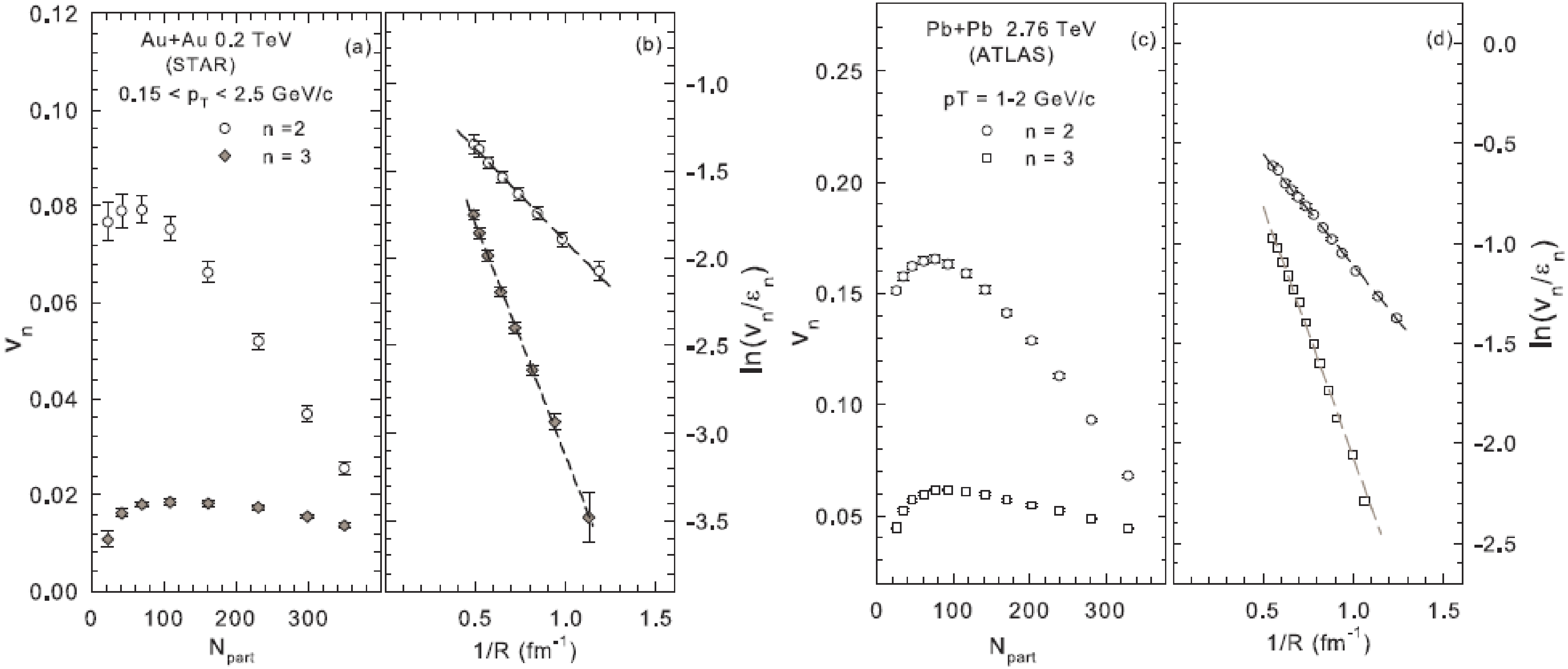
$(R^2_{out}-R^2_{side})$ sensitive to emission duration

Anticipate extended emission duration with 1st order transition

Scaling properties of flow

$$\ln\left(\frac{v_n}{\varepsilon_n}\right) \propto \frac{-\beta''}{\bar{R}}$$

Acoustic Scaling – $\frac{1}{\bar{R}}$



✓ **Characteristic $1/\bar{R}$ viscous damping validated with n^2 dependence at RHIC & the LHC**

✓ **Important constraint for η/s**

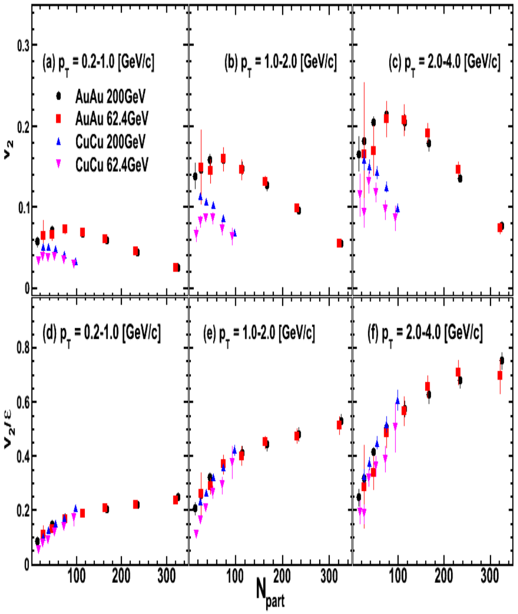
Recent PHENIX publications on flow at RHIC:

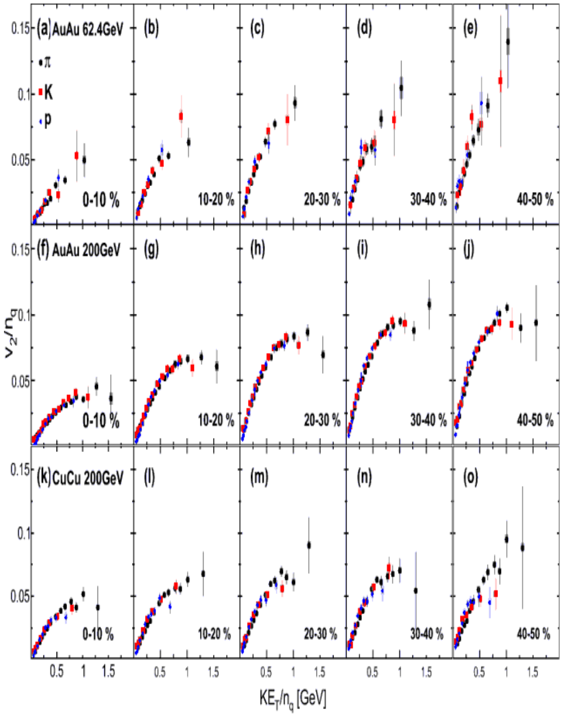
1) **Systematic Study of Azimuthal Anisotropy in Cu+Cu and Au+Au Collisions at 62.4 and 200 GeV:**

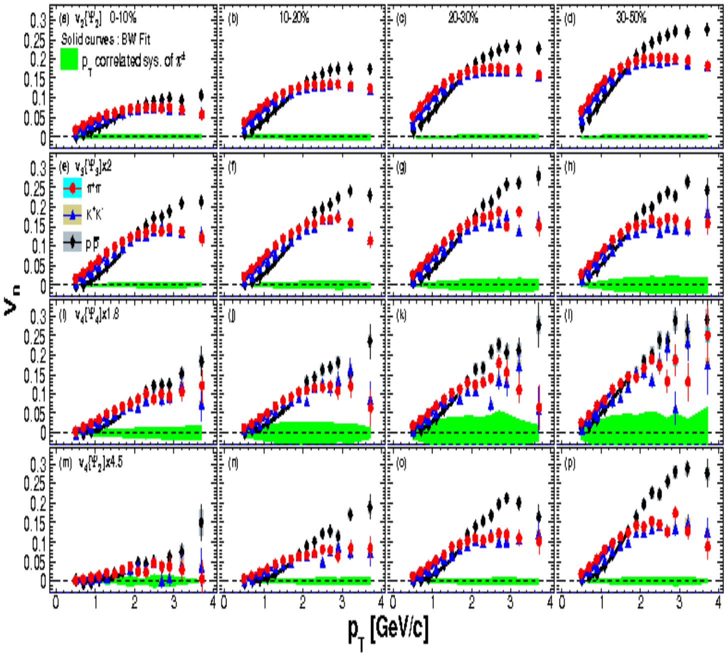
arXiv:1412.1043

2) **Measurement of the higher-order anisotropic flow coefficients for identified hadrons in Au+Au collisions at 200 GeV :**

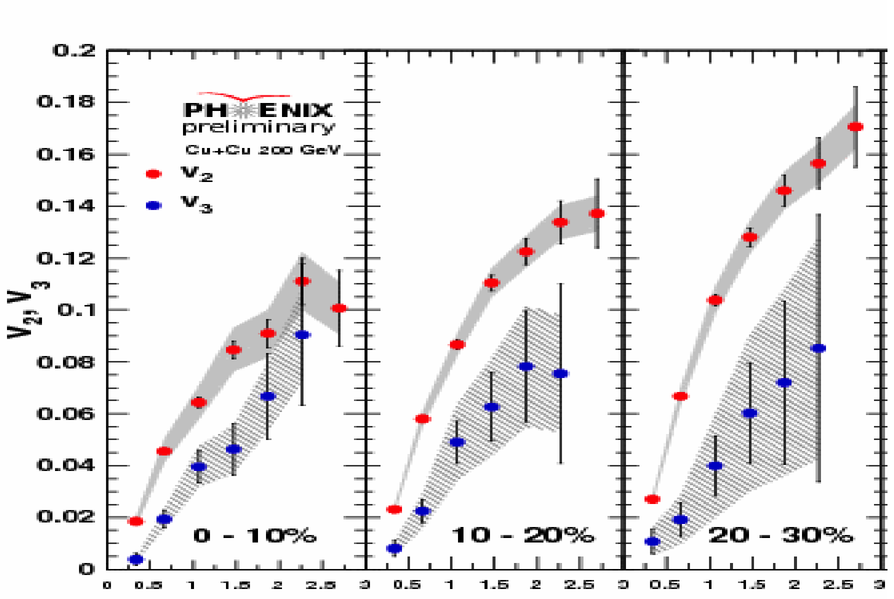
arXiv:1412.1038



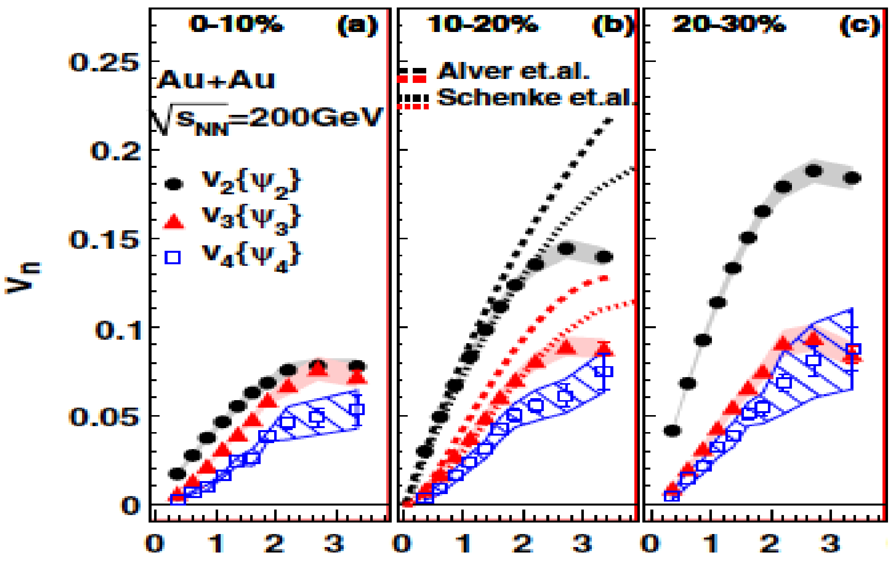




Flow in symmetric colliding systems : Cu+Cu vs Au+Au



Phys.Rev.Lett. 107 (2011) 252301



Strong centrality dependence of v_2 in AuAu, CuCu

Weak centrality dependence of v_3

Simultaneus measurements of

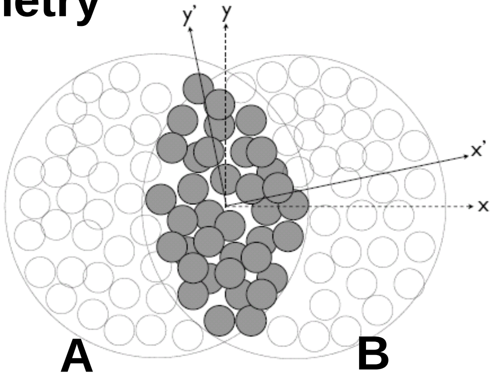
v2 and v3 → Crucial constraint for η/s

Scaling expectation:

$$\frac{v_n(p_T)}{\varepsilon_n} = \alpha \cdot \exp\left(-\beta' n^2\right)$$

Geometric quantities for scaling

Geometry



Phys. Rev. C 81, 061901(R) (2010)

$$S_{nx} \equiv S_n \cos(n\Psi_n^*) = \int d\mathbf{r}_\perp \rho_s(\mathbf{r}_\perp)\omega(\mathbf{r}_\perp)\cos(n\phi)$$

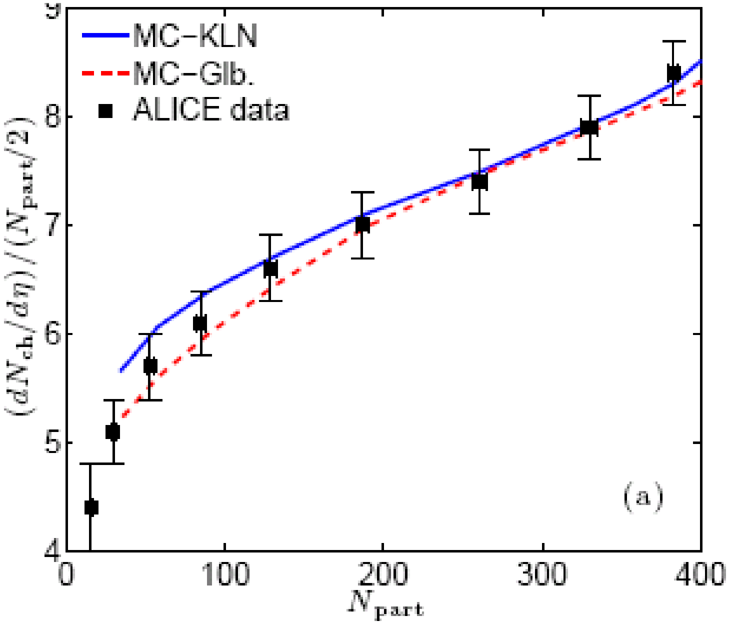
$$S_{ny} \equiv S_n \sin(n\Psi_n^*) = \int d\mathbf{r}_\perp \rho_s(\mathbf{r}_\perp)\omega(\mathbf{r}_\perp)\sin(n\phi),$$

$$\Psi_n^* = \frac{1}{n}\tan^{-1}\left(\frac{S_{ny}}{S_{nx}}\right)$$

$$\varepsilon_n = \left\langle \cos n\left(\phi - \psi_n^*\right)\right\rangle$$

$$\frac{1}{\bar{R}} = \sqrt{\left(\frac{1}{\sigma_x^2} + \frac{1}{\sigma_y^2}\right)}$$

arXiv:1203.3605



σ_x & σ_y → RMS widths of density distributio

- **Geometric fluctuations included**
- **Geometric quantities constrained by multiplicity density.**