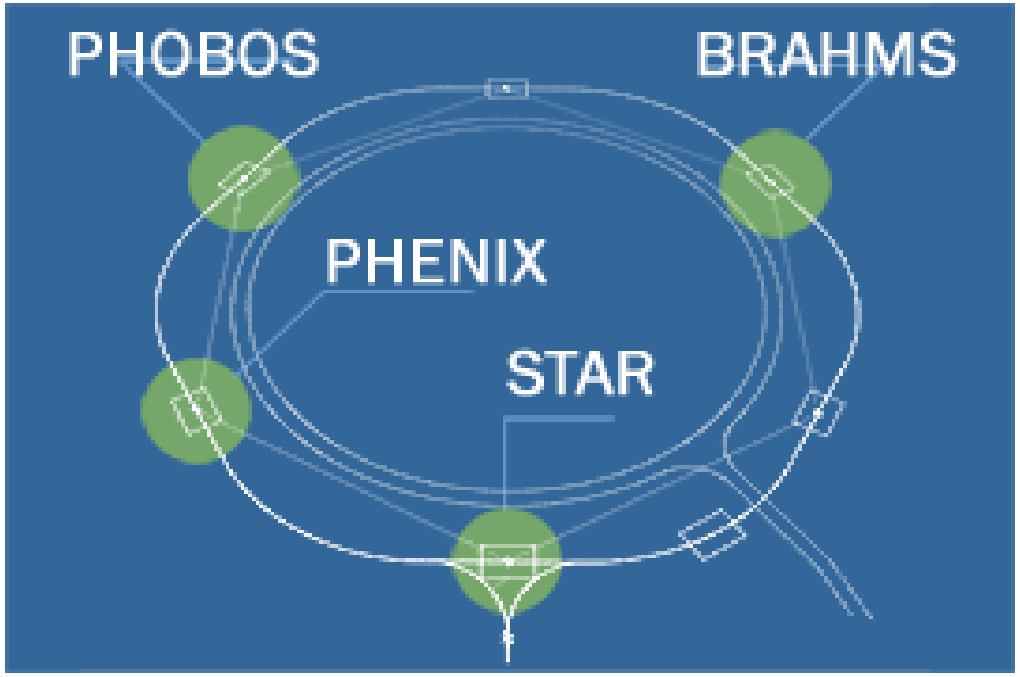
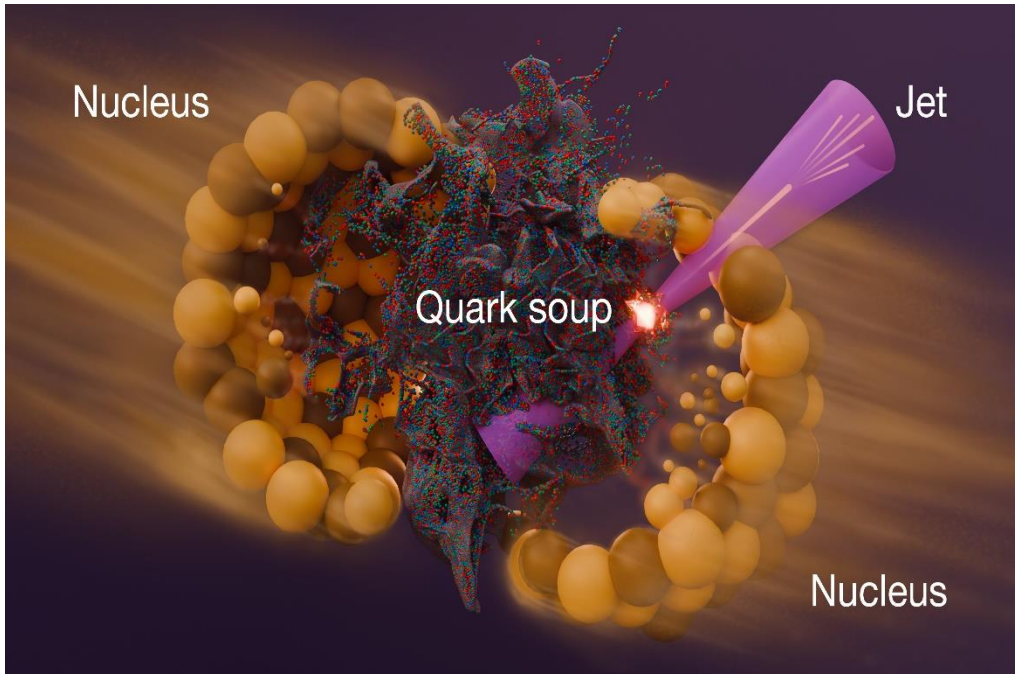
«Анизотропные потоки и свойства сильно-взаимодействующей материи в столкновениях ядер при энергиях коллайдера RHIC»

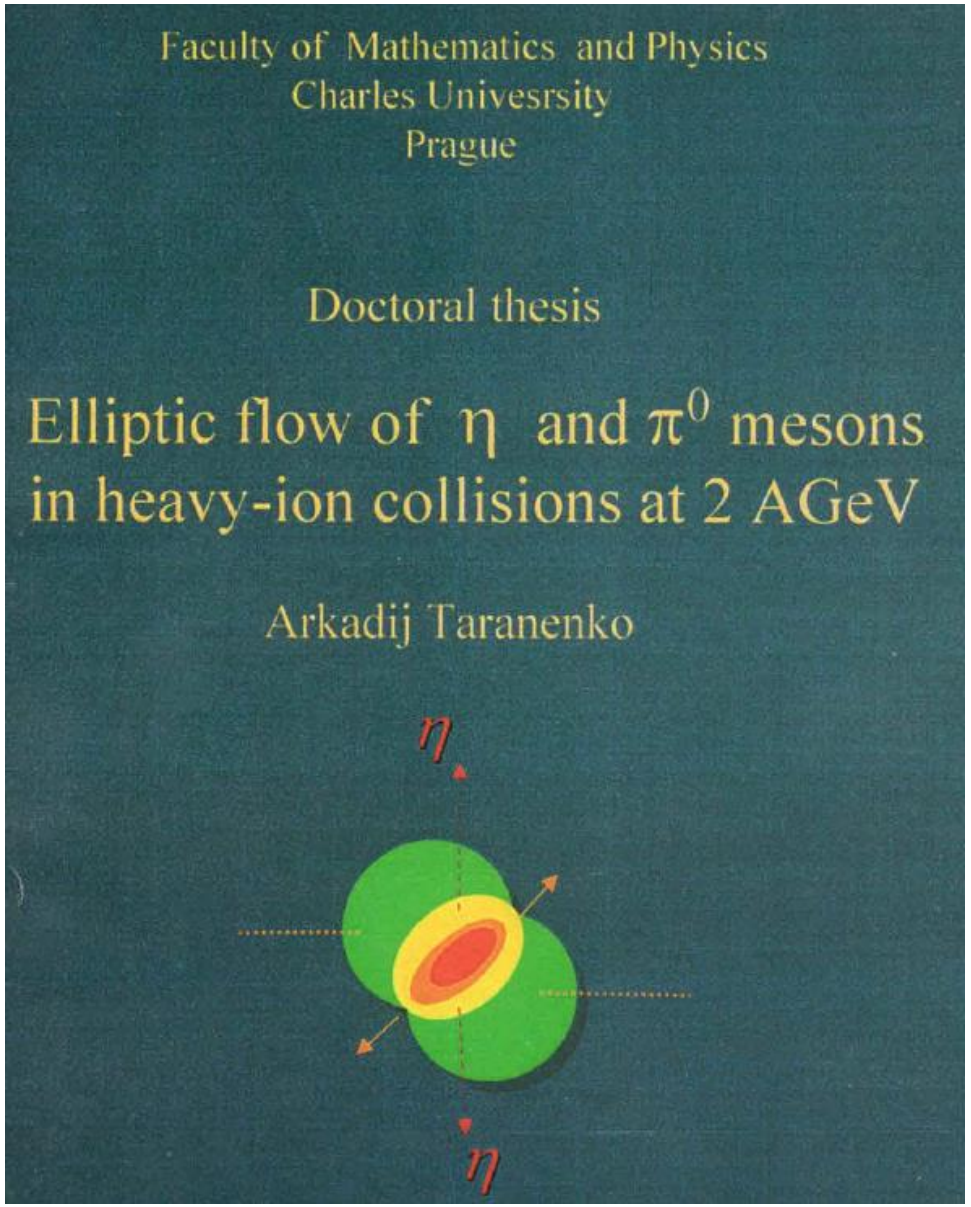




Аркадий Тараненко (ataranenko@jinr.ru)

Общелабораторный семинар ЛФВЭ, 13 марта, 2026

Общелабораторный семинар ЛВЭ, октябрь 1997 года, младший научный сотрудник Тараненко А.В



A. Taranenko et al , Czech J of Phys, Vol. 47 (1997), No. 9, 891-898

We fitted these distributions by a standard formula

$$N(\varphi) = \frac{N_0}{2\pi}\left[1 + S_1 \cos\varphi + S_2 \cos(2\varphi)\right]$$

which is used to describe nuclear flow, see [11]. Here S_1 and S_2 correspond to magnitudes of sideward flow and squeeze-out, respectively. The magnitude of the observed anisotropy can be described by the squeeze-out ratio:

$$R = \frac{\frac{dN}{d\varphi}(90°) + \frac{dN}{d\varphi}(270°)}{\frac{dN}{d\varphi}(0°) + \frac{dN}{d\varphi}(180°)} = \frac{1 - S_2}{1 + S_2}$$

A. Taranenko and A. Kugler, Czech J of Phys, Vol. 50 (2000), Suppl S4, 139-166

We fitted the azimuthal yields of π^0 mesons by the first two terms of a Fourier expansion in the azimuthal angle:

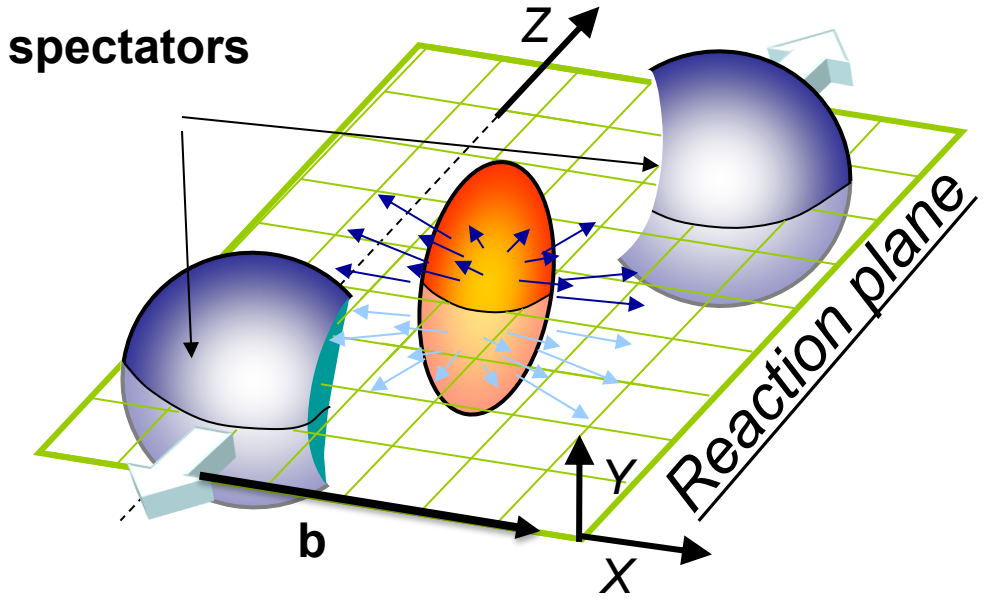
$$N(\Delta\varphi) = \frac{N_0}{2\pi}\left(1 + 2v_1 \cos(\Delta\varphi) + 2v_2 \cos(2\Delta\varphi)\right). \qquad (17)$$

The first coefficient (v_1) is used to parametrize the in-plane emission of the particles parallel ($v_1 > 0$) or antiparallel ($v_1 < 0$) to the impact-parameter vector (directed flow), whereas the second coefficient (v_2) quantifies an elliptic flow, which is negative for out-of-plane emission and positive for an in-plane emission [25, 24]. The

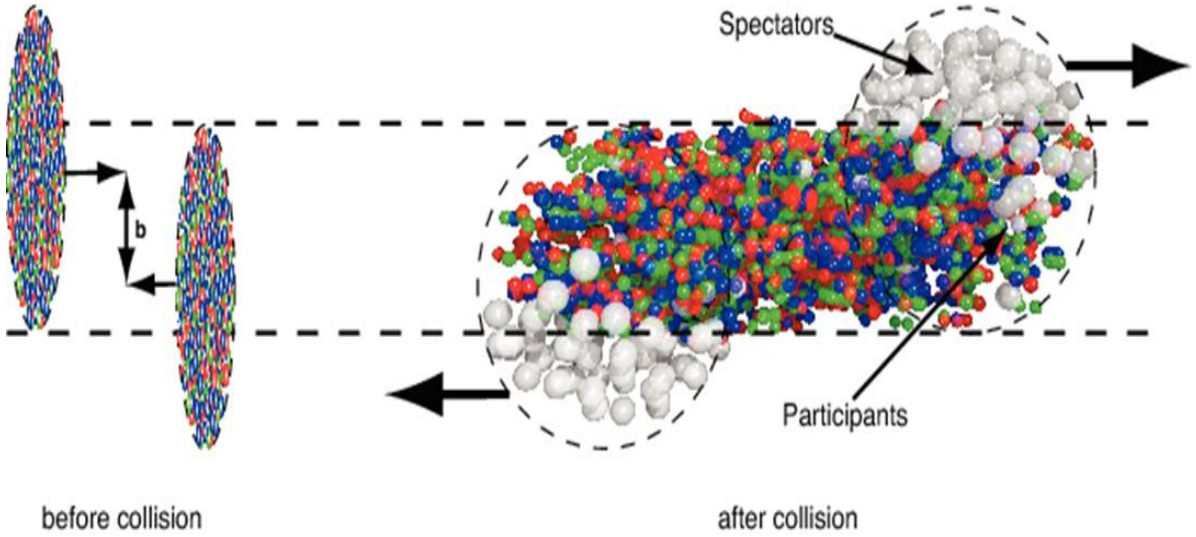
OUTLINE

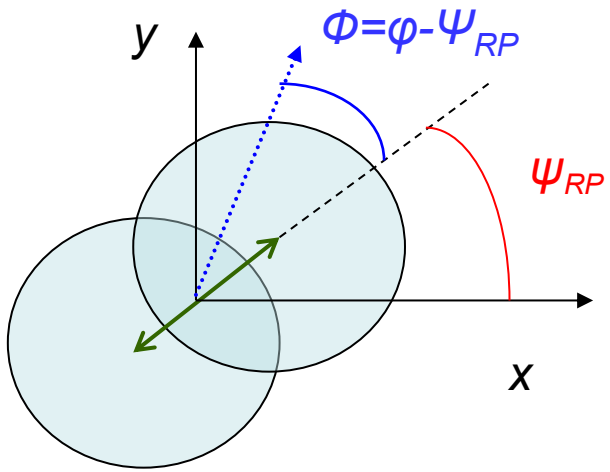
1) Anisotropic flow: Introduction
2) Flow and sQGP at RHIC?
3) Scaling properties of anisotropic flow
4) Flow results from Beam Energy Scans
5) Outlook for flow measurements at NICA

HIC: Impact parameter & Reaction plane

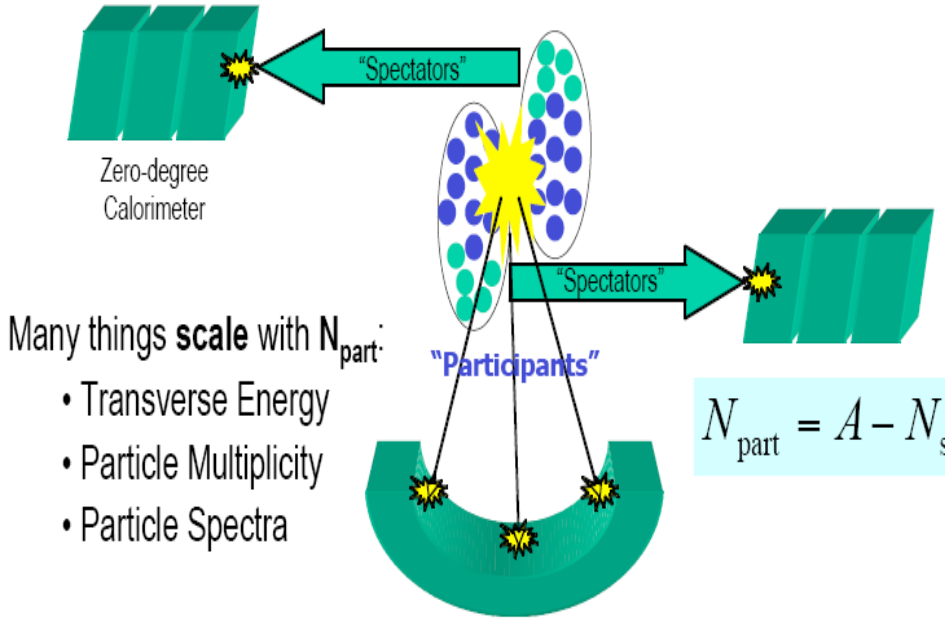


- **Impact parameter b:** ⊥ to the beam direction **(z)**, connects centers of colliding nuclei
- **Reaction plane:** spanned by beam direction (**z**) and impact parameter (**b**)





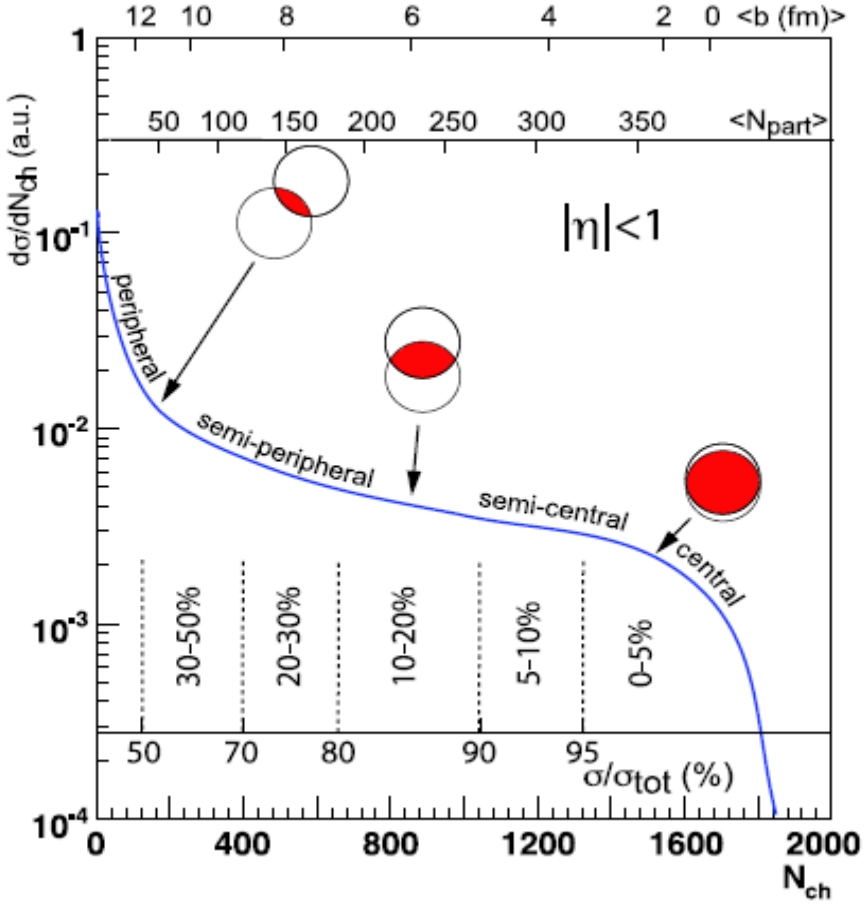
HIC: Centrality of the collision



Many things **scale** with N_{part}:

- Transverse Energy
- Particle Multiplicity
- Particle Spectra

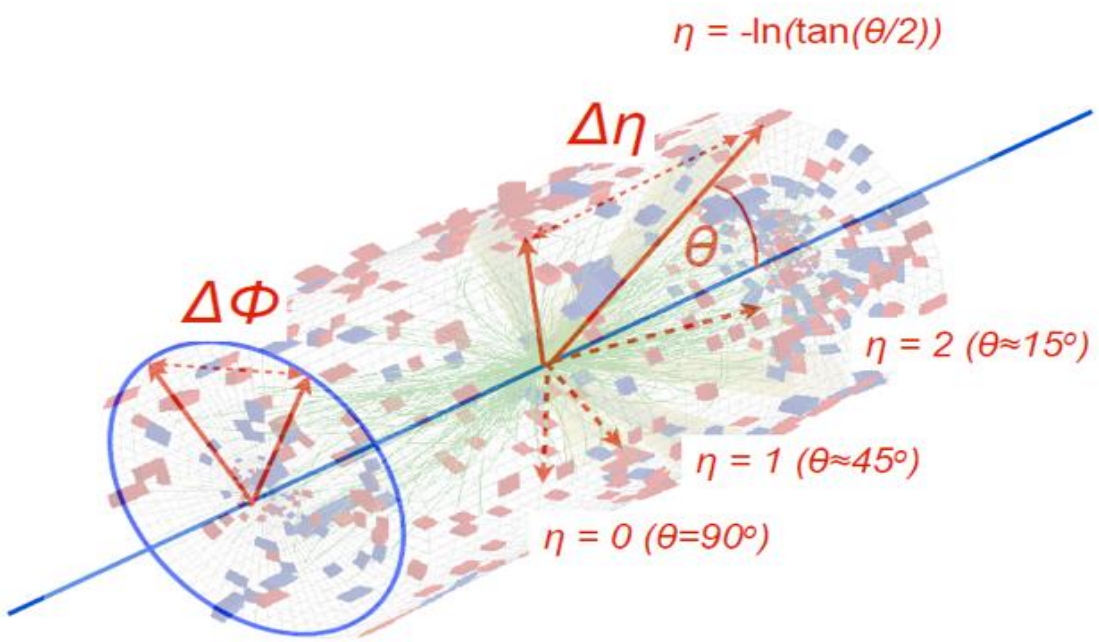
$$N_{\text{part}} = A - N_{\text{spec}}$$



"Centrality classes": percentiles (fraction of total integral) of centrality distribution.

Convention: 0% = most central,
100% = most peripheral
peripheral → low mult, central → high mult

HIC: Angular and kinematical variables



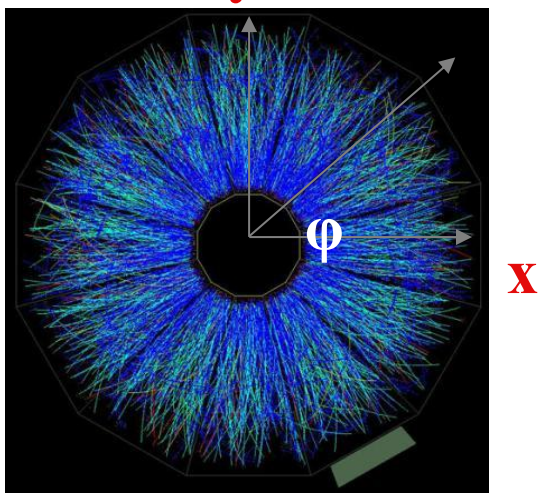
- φ - azimuthal angle
- θ - polar angle
- η - pseudo-rapidity

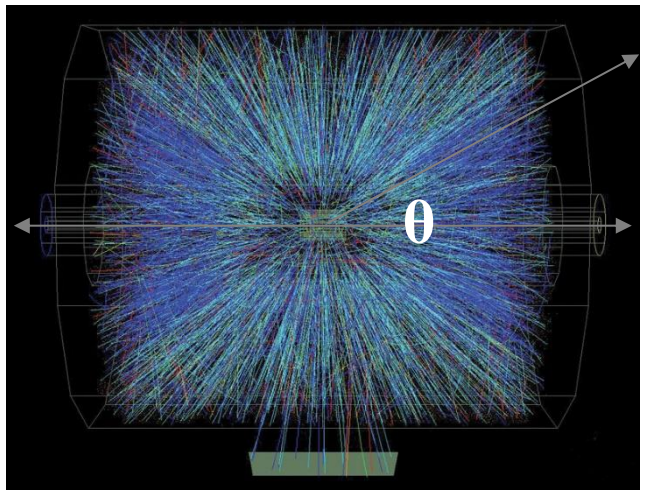
$$\eta = -\ln\left(\tan\left(\frac{\theta}{2}\right)\right)$$

- y – rapidity

$$y = \frac{1}{2}\ln\left(\frac{E + p_z}{E - p_z}\right)$$

- p_T -transverse momentum

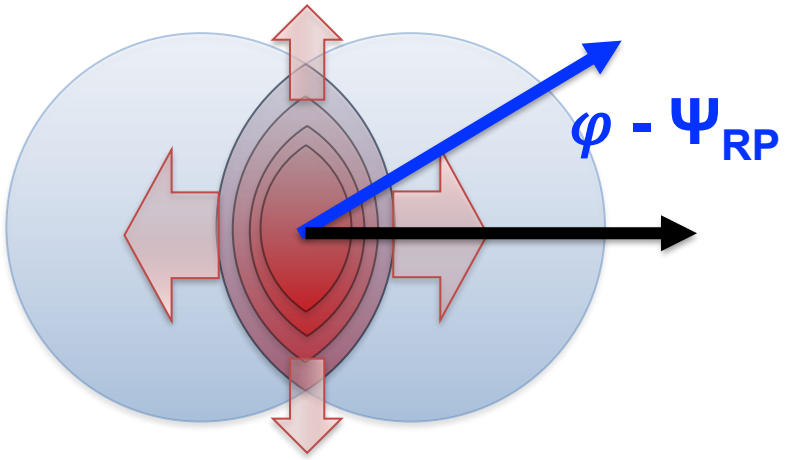




$$p_T = \sqrt{p_x^2 + p_y^2}$$

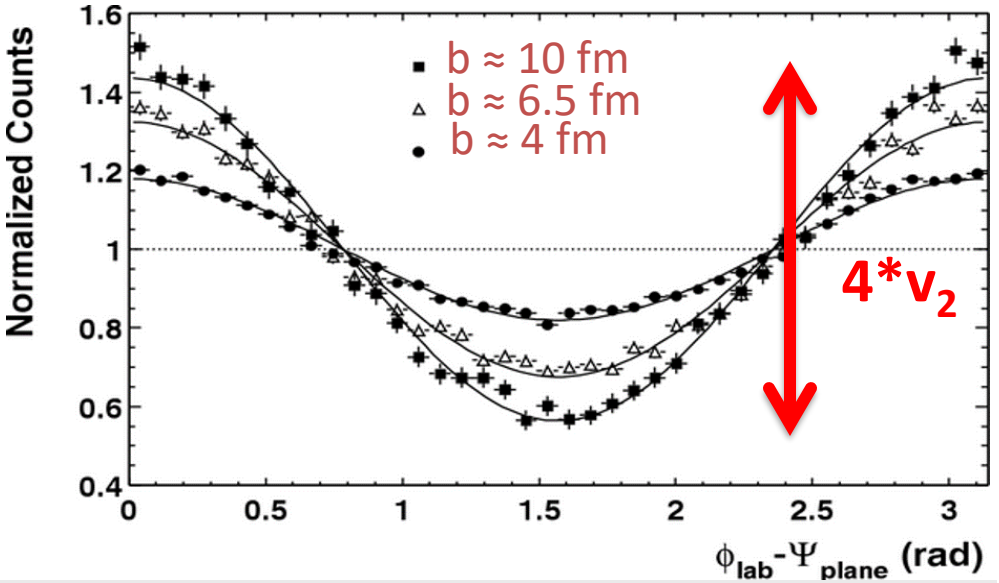
$$m_T = \sqrt{m^2 + p_T^2}$$

Azimuthal anisotropic flow of particles at HIC



Sergei Voloshin, Y. Zhang, Z. Phys. C70,(1996), 665

STAR, PRL**90** 032301 (2003)



$$\frac{dN}{d(\varphi-\Psi_{RP})}=\frac{N_0}{2\pi}\left(1+2v_1\cos(\varphi-\Psi_{RP})+2v_2\cos(2(\varphi-\Psi_{RP}))+....\right)$$

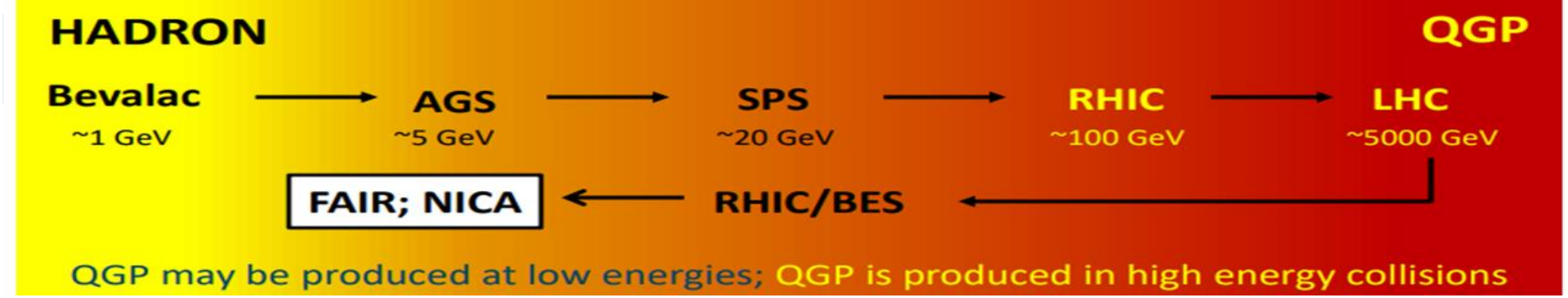
- The sinus terms are skipped by symmetry arguments
- From the properties of Fourier's series one has

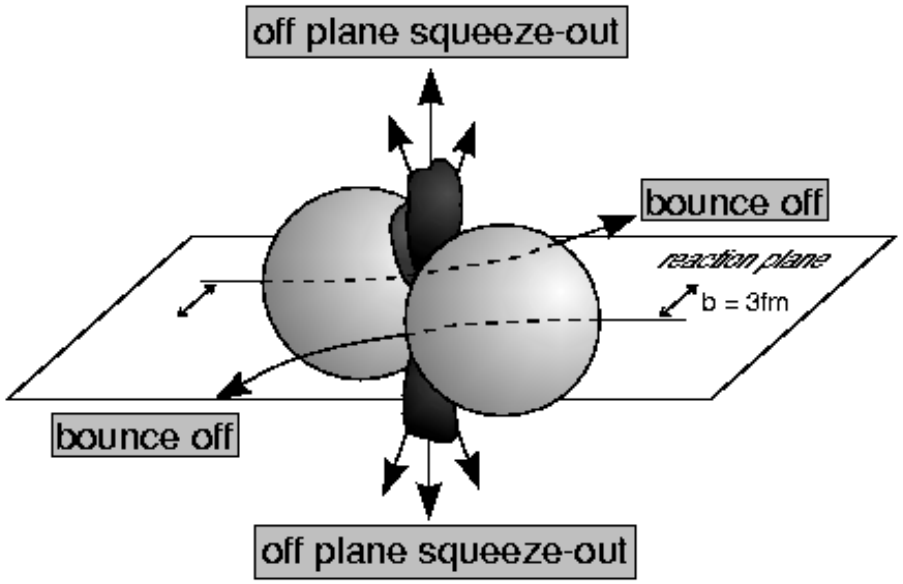
$$v_n=\langle\cos[n(\varphi-\Psi_{RP})]\rangle$$

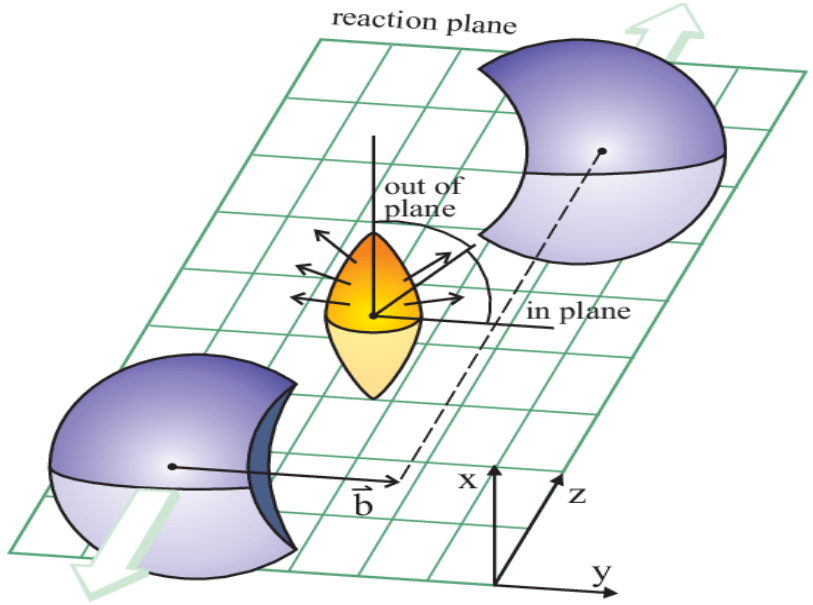
- Fourier coefficients $\mathbf{V_n}$ quantify anisotropic flow:

v_1 is directed flow, v_2 is elliptic flow, v_3 is triangular flow, etc.

Term "flow" does not mean necessarily "hydro" flow – used only to emphasize the collective behavior of particles in event or multiparticle azimuthal correlation





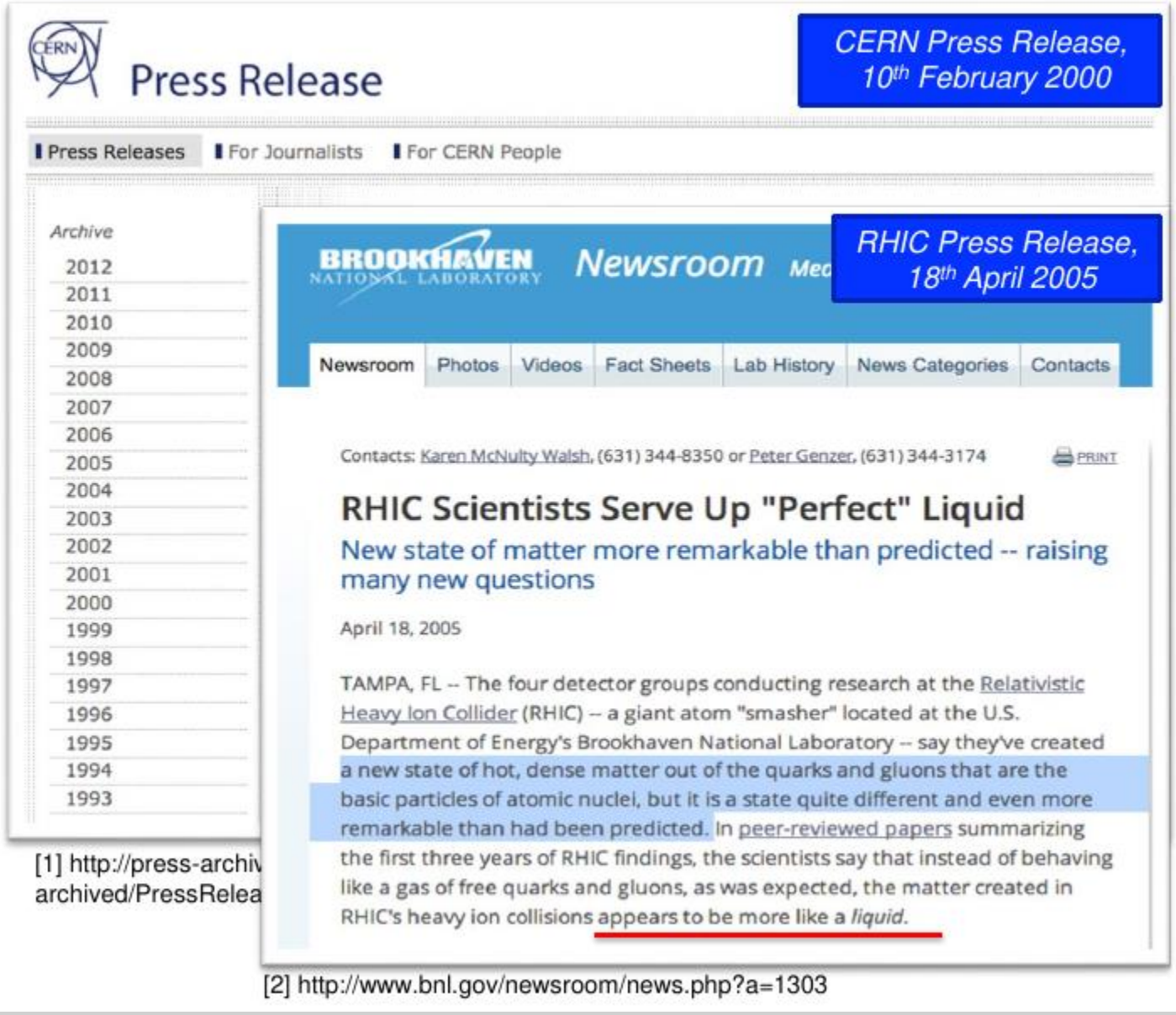


Anisotropic Flow in Heavy-Ion Collisions > 35 years

Plastic Ball, H.H. Gutbrod et al., Phys. Lett. B216, 267 (1989)

Diogene, M. Demoulins et al., Phys. Lett. B241, 476 (1990)

Perfect Liquid Discovered at RHIC: 2005



[1] http://press-archiv
archived/PressRelea

[2] http://www.bnl.gov/newsroom/news.php?a=1303

First "compelling" evidence of QGP at SPS

The "remarkable" evidence at RHIC that the hot matter formed is

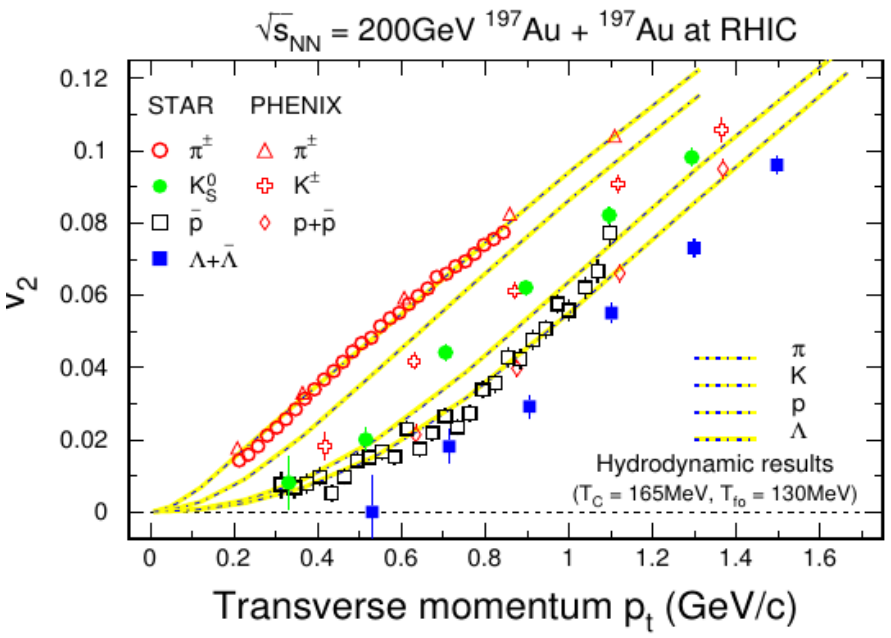
- Extremely **strongly interacting (sQGP)**

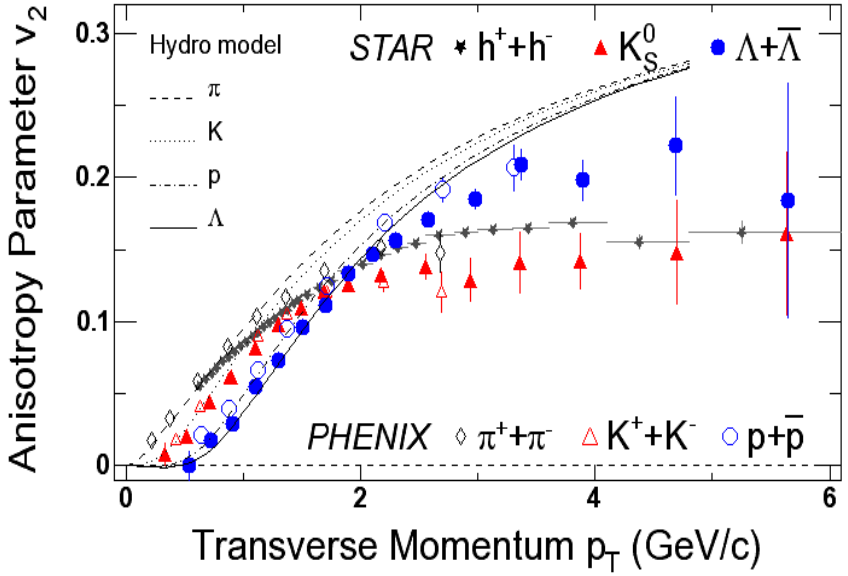
- Absorbing energy of traversing partons → **Almost opaque medium**

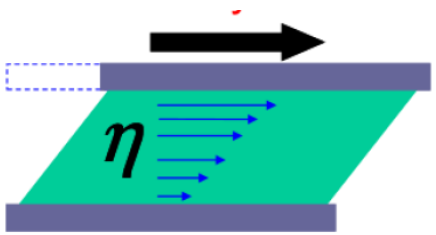
- Reacting to pressure gradients by flowing with very small shear viscosity → **Almost perfect liquid**

Large V_2 at RHIC = sQGP - Change of paradigm

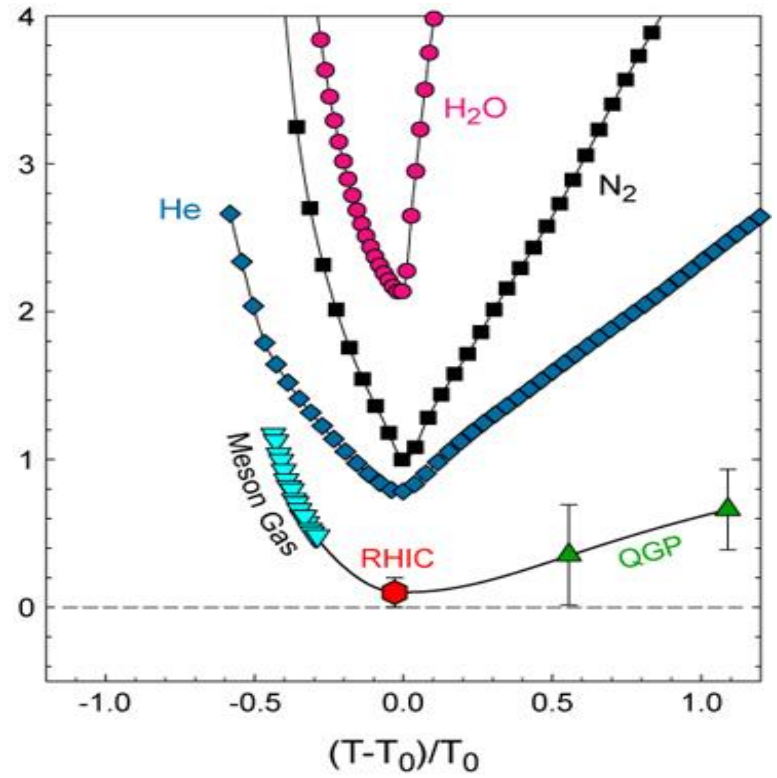
STAR : PRC 72, 014904 (2005)







R. Lacey, A. Taranenko et. al, PRL.98:092301,2007



- Manifestation of strongly coupled QGP
- Not a gas of free quarks and gluons
- Instead, strongly coupled nearly perfect liquid reaching almost the minimum value of shear viscosity to entropy density ratio (η/s)

Scaling properties of collective flow

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

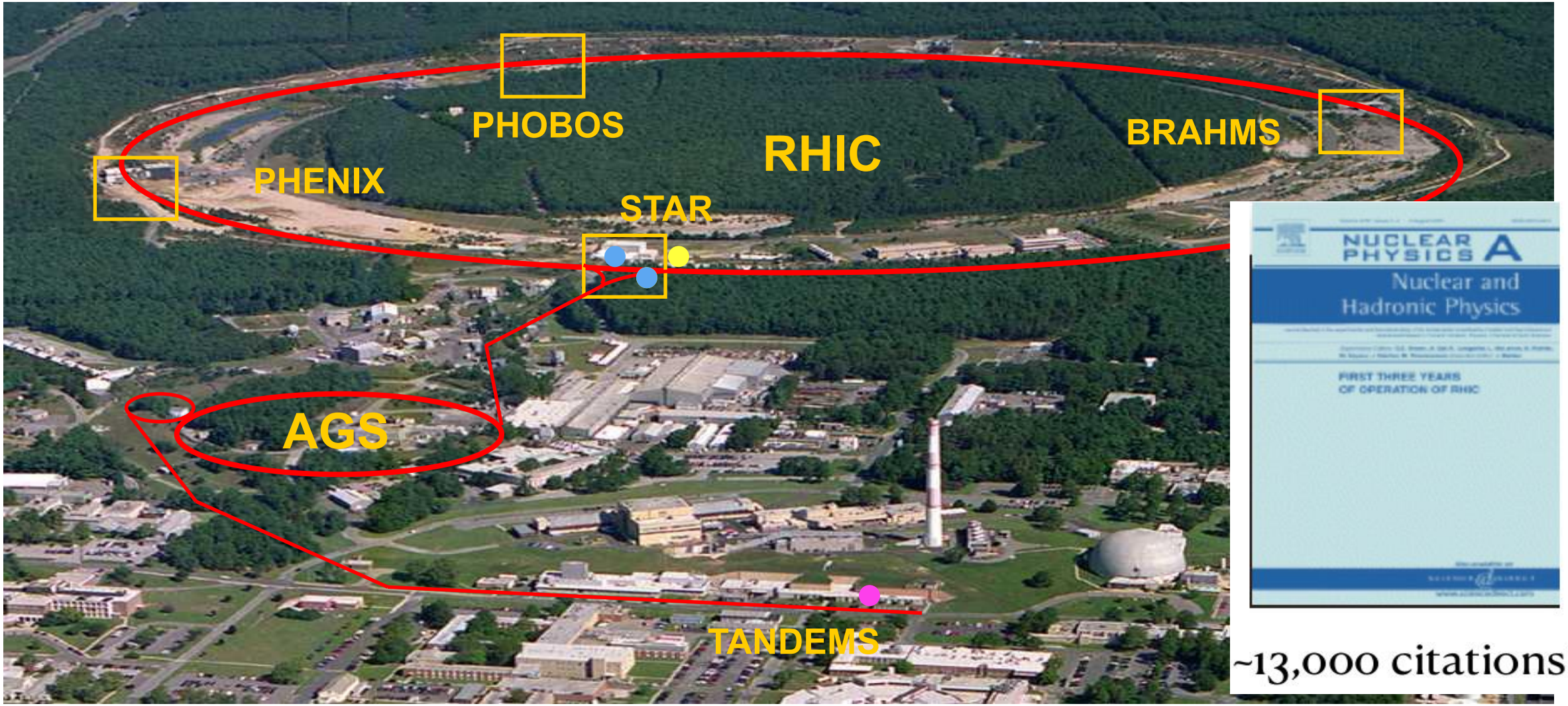
The general features of the collective flow could, in principle, be expressed in terms of scale-invariant quantities. In this way the particular differences arising from the different initial conditions, masses, energies, etc. , can be separated from the general fluid-dynamical features

"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. …The evolution in non-viscous hydrodynamics does not depend on the size of the system nor on the incident energy, if distances are rescaled in terms of a typical size parameter, such as the nuclear radius. Momenta and energies are rescaled in terms of the beam velocities, momenta or energies.

The proposal to look for scaling relations and use them – is very – very old !!!!

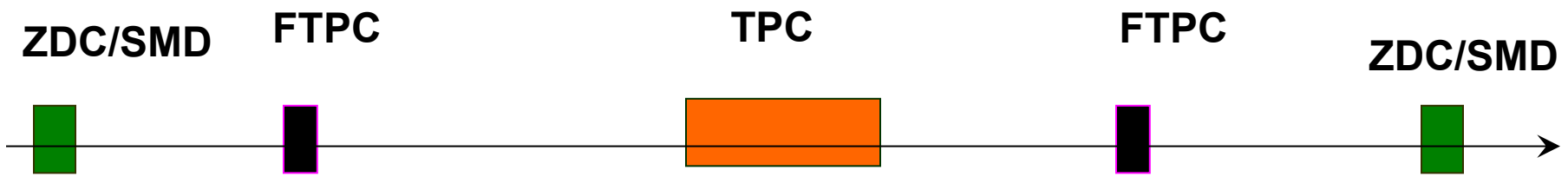
Relativistic Heavy Ion Collider (RHIC): 2000-2026



2005: Quark-Gluon Matter (Plasma) is a "perfect liquid"

Anisotropic Flow Measurements V_2 (p_T, centrality) in STAR/PHENIX

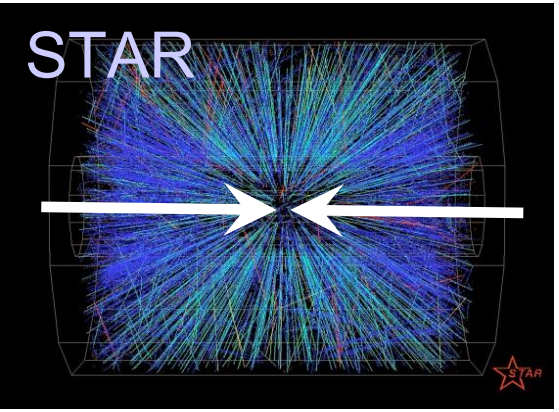
STAR

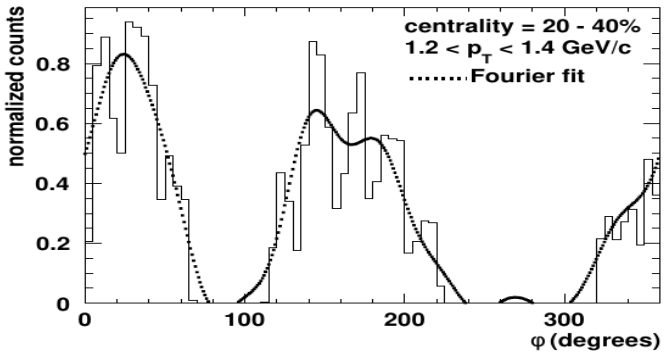


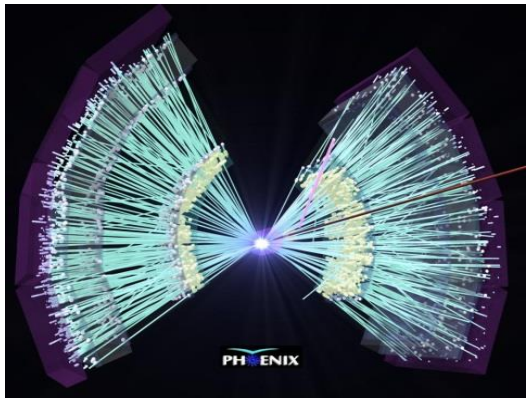
|η| < 1.3

2.5 <|η|< 4.0

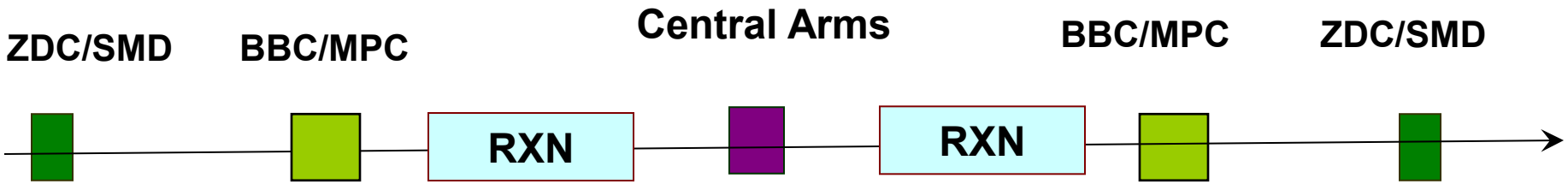
|η| > 6.3







PHENIX



1.0<|η|<2.8

|η|<0.35

3.1<|η|<3.7

3.1<|η|<3.9

|η| > 6.6



Selected publications: 2005-2018 (Anisotropic Flow at RHIC)

1) Saturation of azimuthal anisotropy in Au + Au collisions at 62.4 – 200 GeV, S.S. Adler, A. Taranenko et. al. (PHENIX), Phys. Rev. Lett. 94 (2005) 232302
2) Formation of dense partonic matter in relativistic nucleus-nucleus collisions at RHIC: Experimental evaluation by the PHENIX collaboration, K. Adcox, A. Taranenko et.al (PHENIX), Nucl. Phys. A 757 (2005) 184-283
3) Scaling properties of azimuthal anisotropy of mesons and baryons at RHIC, A. Taranenko, Acta Phys. Hung. A 25 (2006) 371-379
4) What do elliptic flow measurements tell us about the matter created in the little bang at RHIC?, R.A. Lacey, A. Taranenko, PoS CFRNC2006 (2006) 021
5) Has the QCD Critical Point been Signaled by Observations at RHIC?, R. A. Lacey, A. Taranenko, Phys. Rev. Lett. 98 (2007) 092301
6) Scaling properties of azimuthal anisotropy in Au+Au and Cu+Cu collisions at 200 GeV, A. Adare, A. Taranenko (PHENIX), Phys.Rev. Lett. 98 (2007) 162301
7) PHENIX studies of the scaling properties of elliptic flow at RHIC, A. Taranenko, J. Phys. G 34 (2007) S1069-1072
8) Elliptic flow for phi mesons and (anti)deuterons in Au + Au collisions at 200 GeV, S. Afanasiev, A. Taranenko et. al. (PHENIX), Phys. Rev. Lett. 99 (2007) 052301
9) Systematic Studies of Elliptic Flow Measurements in Au+Au Collisions at 200 GeV, S. Afanasiev, A. Taranenko et. al. (PHENIX), Phys. Rev. C 80 (2009) 024909
10) Constraints on models for the initial collision geometry in ultra relativistic heavy ion collisions, R. A. Lacey, A. Taranenko, Phys. Rev. C 81 (2010) 061901
11) Elliptic and hexadecapole flow of charged hadrons in Au+Au collisions at 200 GeV, A. Adare, A. Taranenko et. al. (PHENIX), Phys. Rev. Lett. 105 (2010) 062301
12) Azimuthal anisotropy: transition from hydrodynamic flow to jet suppression, R. A. Lacey, A. Taranenko, Phys. Rev. C 82 (2010) 034910
13) Initial indications for the production of a strongly coupled plasma in Pb+Pb collisions at 2.76 TeV, R. A. Lacey, A. Taranenko, Phys. Rev. C 83 (2011) 031901
14) Initial eccentricity fluctuations and their relation to higher-order flow harmonics, R. A. Lacey, A. Taranenko, Phys. Rev. C 83 (2011) 044902
15) Beam Energy Dependence of Azimuthal Anisotropy at RHIC-PHENIX, A. Taranenko, Phys. Atom. Nucl. 75 (2012) 550-555
16) Azimuthal anisotropy of $\pi 0$ and η mesons in Au + Au collisions at 200 GeV, A. Adare, A. Taranenko et. al. (PHENIX), Phys. Rev. C 88 (2013) 6, 064910
17) Beam energy dependence of the viscous damping of anisotropic flow in relativistic heavy ion collisions, R.A. Lacey, A. Taranenko, Phys. Rev. Lett. 112 (2014) 8, 082302
18) Systematic Study of Azimuthal Anisotropy in Cu++Cu and Au++Au Collisions at 62.4-200 GeV, A. Adare, A. Taranenko et al.(PHENIX), Phys. Rev. C 92 (2015) 3, 034913
19) Measurement of the higher-order anisotropic flow coefficients for identified hadrons in Au+Au collisions at 200 GeV, A. Adare, A. Taranenko et al.(PHENIX), Phys. Rev. C 93 (2016) 5, 051902
20) Acoustic scaling of anisotropic flow in shape-engineered events: implications for extraction of the specific shear viscosity of the quark gluon plasma, R.A. Lacey, A. Taranenko J. Phys. G 43 (2016) 10, 10LT01
21) Are flow measurements at RHIC reliable? A. Taranenko, J.Phys.Conf.Ser. 668 (2016) 1, 012081
22) PHENIX Measurements of Correlations at RHIC, A. Taranenko, J.Phys.Conf.Ser. 668 (2016) 1, 012029
23) Anisotropic Flow Measurements at RHIC, A. Taranenko, KnE Energ.Phys. 3 (2018) 178-187
24) Anisotropic flow measurements from RHIC to SIS, A. Taranenko, EPJ Web Conf. 204 (2019) 03009
25) Results from the RHIC Beam Energy Scan, A. Taranenko, EPJ Web Conf. 164 (2017) 06005

14

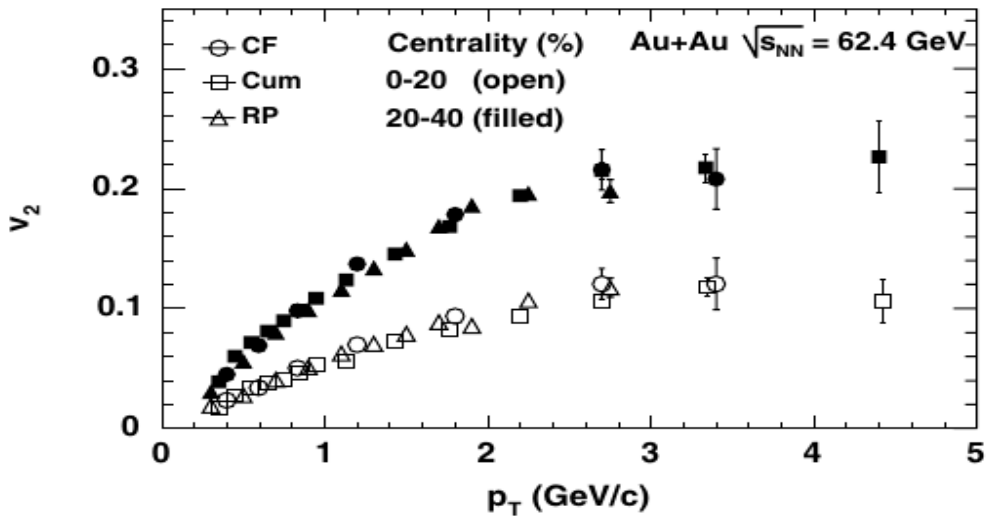
Analysis Notes of Arkadiy Taranenko (PHENIX Collaboration 2003-2016)

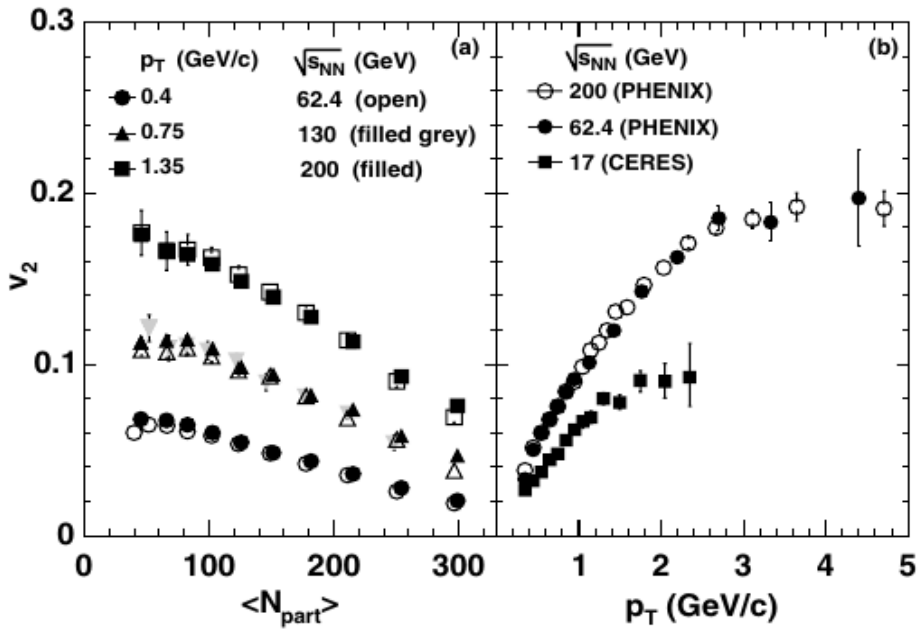
Wednesday Mar 11, 2026, 10:00 AM → 7:20 PM Europe/Moscow

1. AN235, "Hadron identification in EMC (PbSc)", 2003
   - AN235EmcTOFTa...
   - AN235EmcTOFTa...
2. AN297 "Azimuthal Anisotropy Measurements at 62.4 GeV using cumulants of multiparticle azimuthal correlations", 2004
   - AN297AuAu62Ge...
3. AN338, "Scaling Properties of the Azimuthal Anisotropy of Identified Charged Particles", 2004
   - AN338Au200Scal...
4. AN339, "Flavor Scaling of Azimuthal Anisotropy: unveiling the fine structure of v2", 2004
   - AN339FineStruct...
5. AN 421,"Model-Independent Extraction of Source Images in d+Au and Au+Au Collisions", 2004
   - AN421AuAuImagi...
6. AN441, "Scaling Properties of the Azimuthal Anisotropy in Au+Au and Cu+Cu collisions", 2005
   - AN441ScalingAu...
7. AN491, "Azimuthal Anisotropy of φ mesons in Au+Au collisions at 200 GeV", 2006
   - AN491AuAuv2phi...
8. AN493, "Elliptic flow of φ mesons and (anti-)deuterons in Au+Au collisions at 200 GeV", 2006
   - AN493Auv2deute...
9. AN532, "Scaling Properties of elliptic flow in Cu+Cu collisions at 200 GeV", 2007
   - AN532NqScaling...
10. AN680, "Universal scaling of elliptic and hexadecapole flow in Au+Au collisions at 200 GeV", 2008
    - AN680Auv4pidTa...
11. AN712, "Glauber Calculations of Centrality Dependent Variables in Au+Au collisions at 200 GeV", 2009
    - AN712GlauberAu...
12. AN760, "Measurements of elliptic and hexadecapole flow in Au+Au collisions", 2009
    - AN760Auv2v4cha...
13. AN869, "Elliptic flow of charged hadrons in Au+Au collisions at 200 GeV: Detailed comparison of PHENIX and STAR results", 2010
    - AN869v2PHENIX...
14. AN 957, "Systematic study of azimuthal anisotropy of charged hadrons in Au+Au collisions at 39-62.4 GeV", 2011
    - AN957Auv2h39-6...
15. AN985, "Elliptic flow of identified charged hadrons in Au+Au collisions at 39-62.4 GeV", 2012
    - AN985AuPID39-6...
16. AN1172, "Elliptic and triangular flow of charged hadrons in Au+Au collisions at 39-200 GeV", 2016
    - AN1172v2v3PIDA...

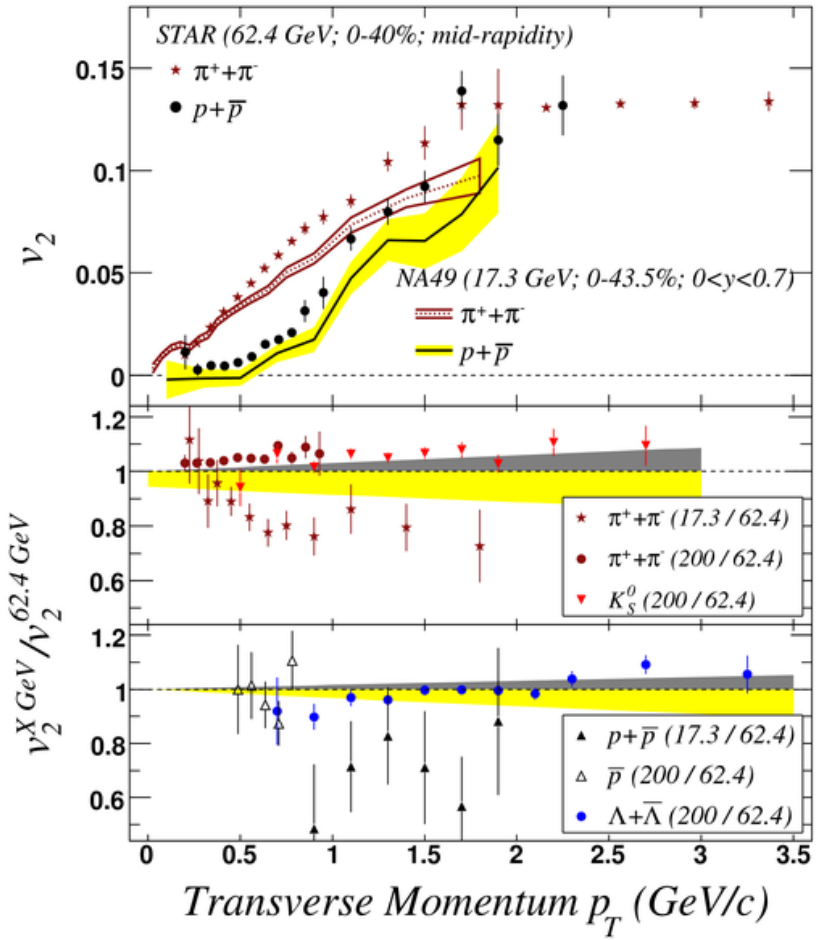
16 Analysis Notes (> 850 pages) https://indico.jinr.ru/event/5992/

Saturation of Azimuthal Anisotropy in Au + Au Collisions at $\sqrt{s_{NN}}$ = 62–200 GeV



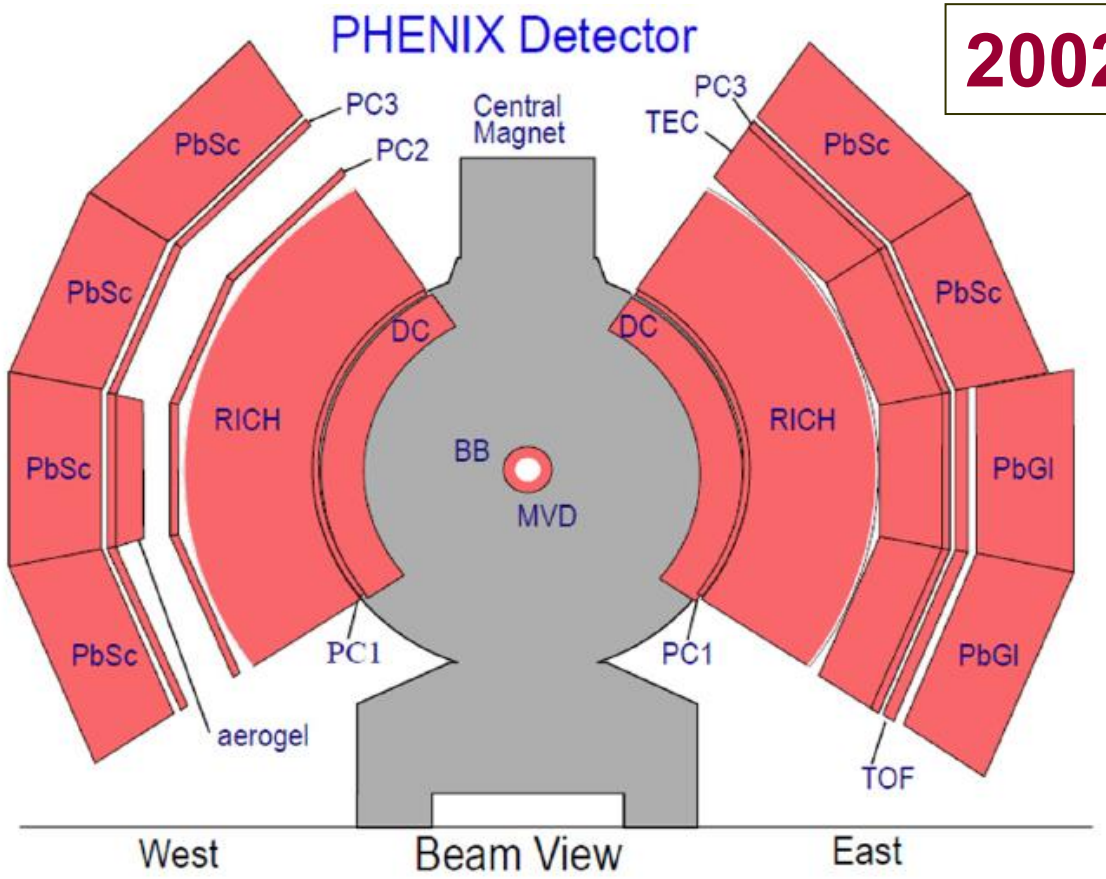


STAR, Phys. Rev. C75 (2007) 054906

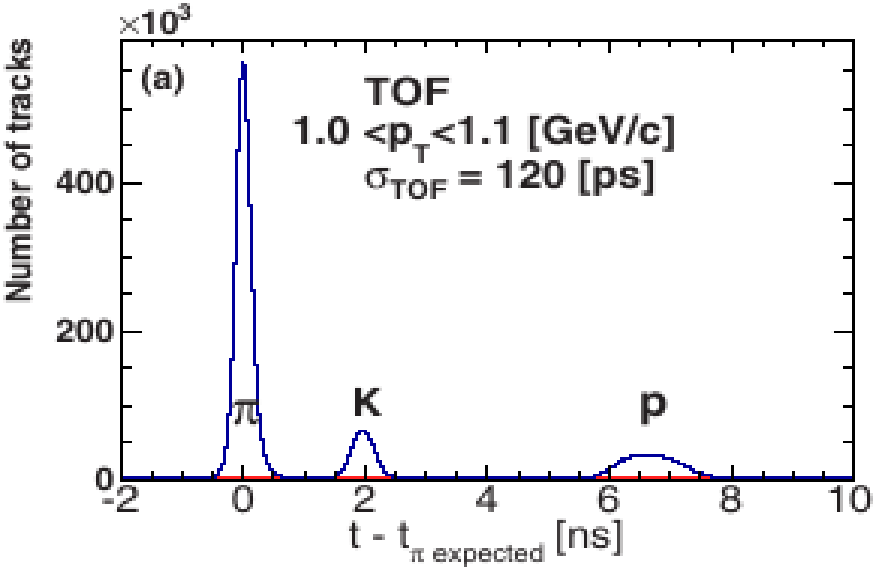


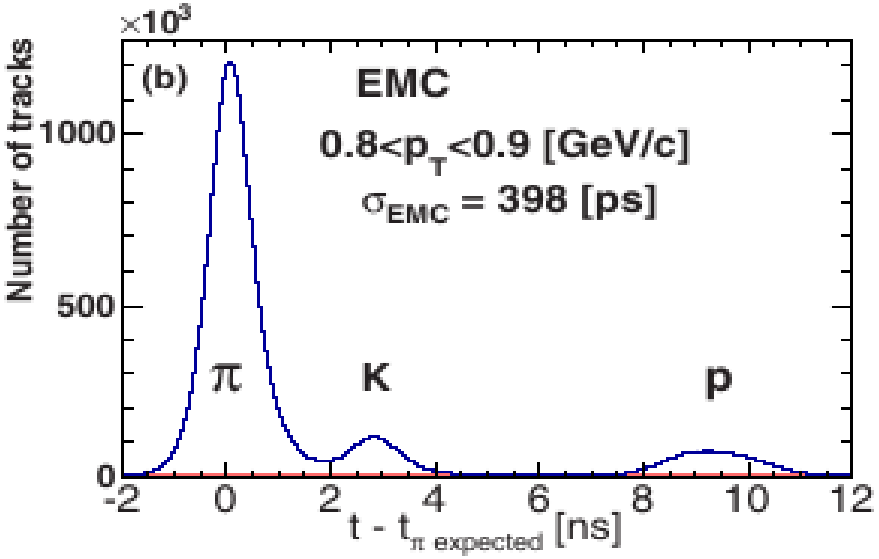
PHENIX (RHIC) 62.4-200 GeV - CERES (SPS) 17.3 GeV : 50% difference

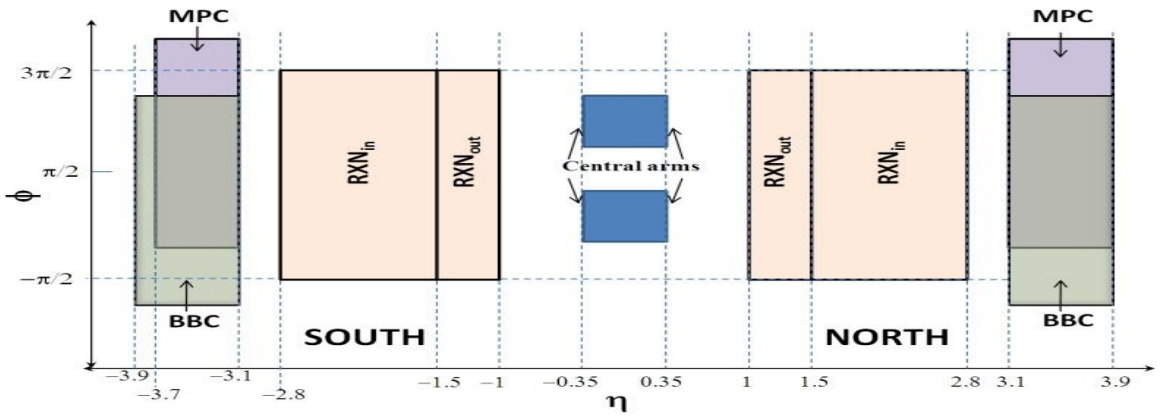
STAR (RHIC) 62.4-200 GeV - NA49 (SPS) 17.3 GeV: 10-25% difference


PHENIX Detector
PC3
Central Magnet
PC3
TEC
PC2
PbSc
PbSc
PbSc
PbSc
PbSc
PbSc
RICH
RICH
DC
DC
BB
MVD
PbGl
PbGl
PC1
PC1
aerogel
TOF
West
Beam View
East

2002-2007


×10³
(a)
TOF
1.0 <p_T<1.1 [GeV/c]
σ_TOF = 120 [ps]
Number of tracks
400
200
0
π
K
p
-2
0
2
4
6
8
10
t - t_π expected [ns]

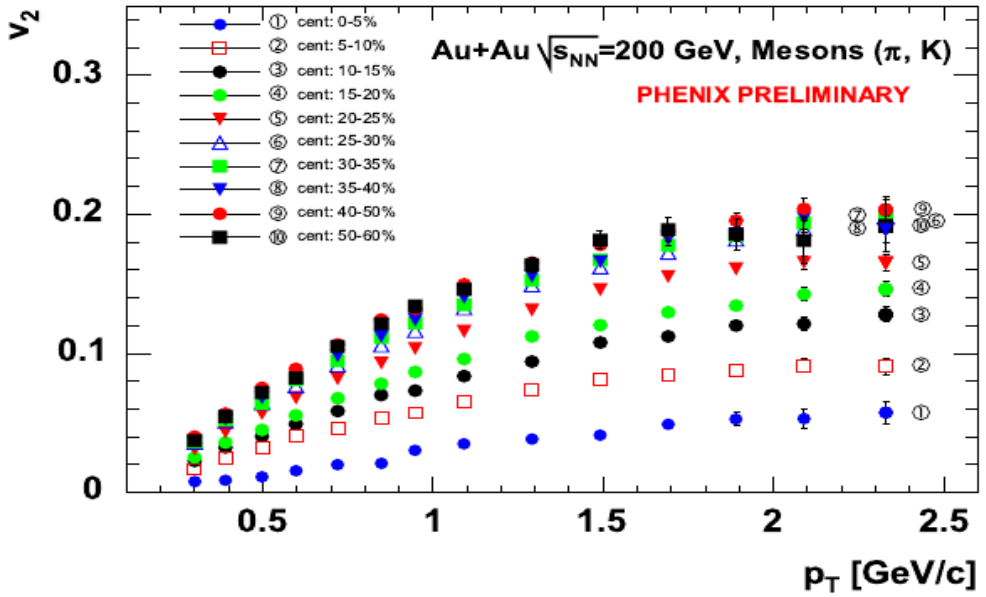

×10³
(b)
EMC
0.8<p_T<0.9 [GeV/c]
σ_EMC = 398 [ps]
Number of tracks
1000
500
0
π
K
p
-2
0
2
4
6
8
10
12
t - t_π expected [ns]

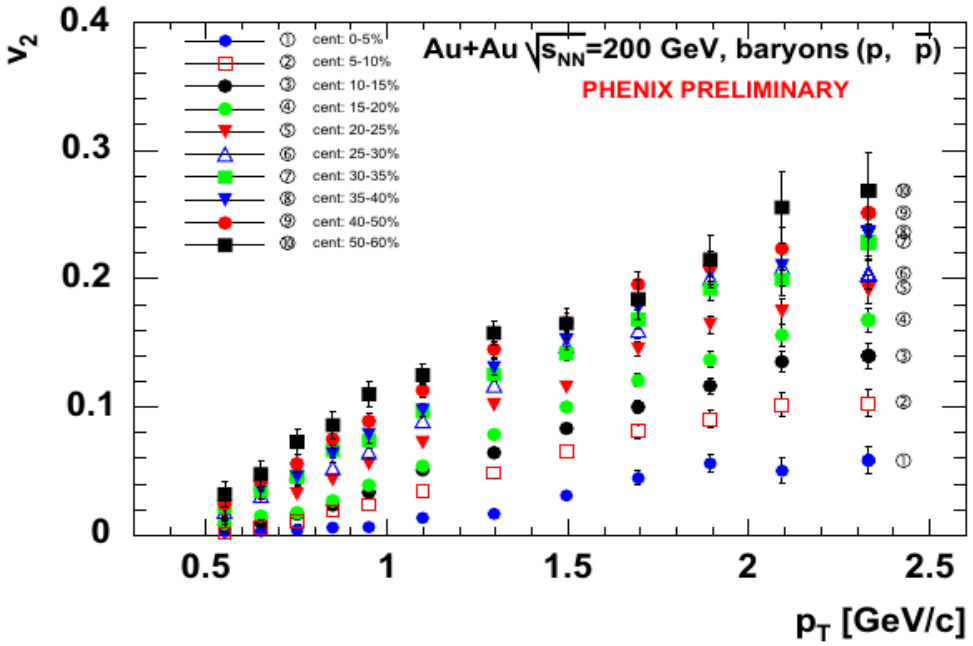

MPC
MPC
3π/2
π/2
−π/2
φ
RXN_in
RXN_out
Central arms
RXN_out
RXN_in
BBC
BBC
SOUTH
NORTH
−3.9
−3.7
−3.1
−2.8
−1.5
−1
−0.35
0.35
1
1.5
2.8
3.1
3.9
η

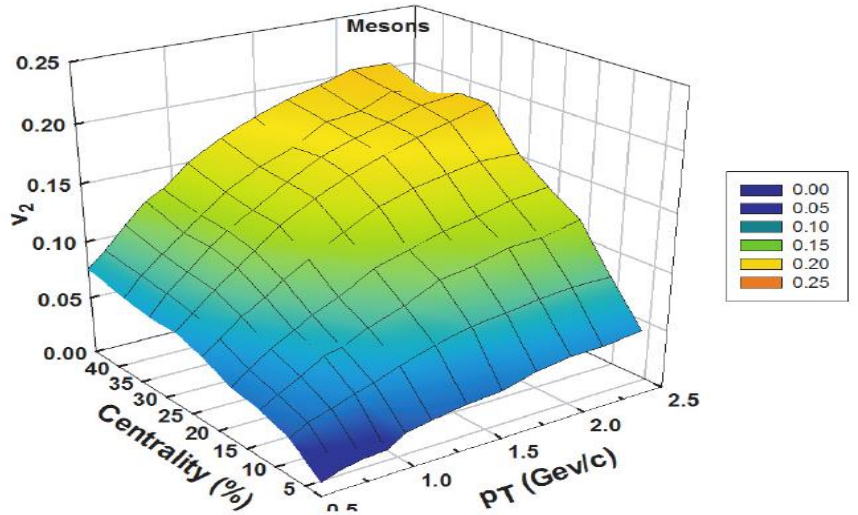
Scaling properties of azimuthal anisotropy of mesons and baryons at RHIC,

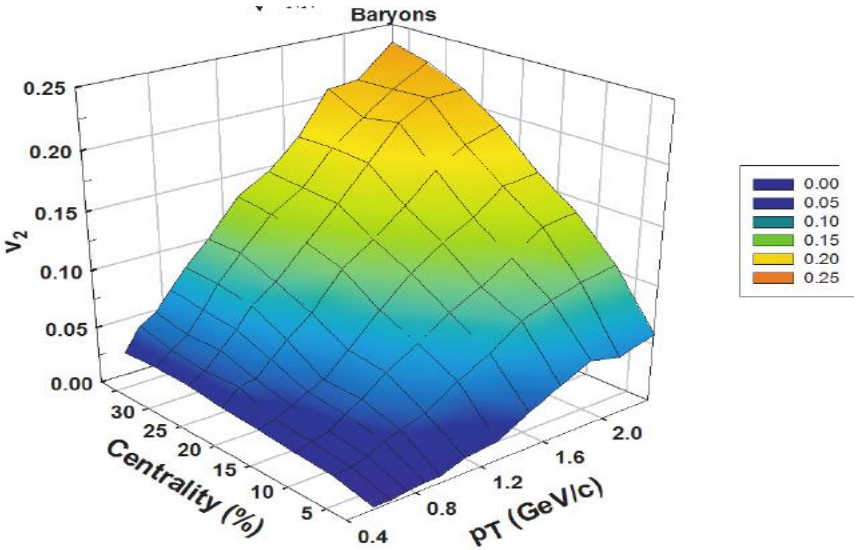
A. Taranenko, Acta Phys. Hung. A 25 (2006) 371-379

Fall 2004 DNP meeting of the American Physical Society, Chicago, IL





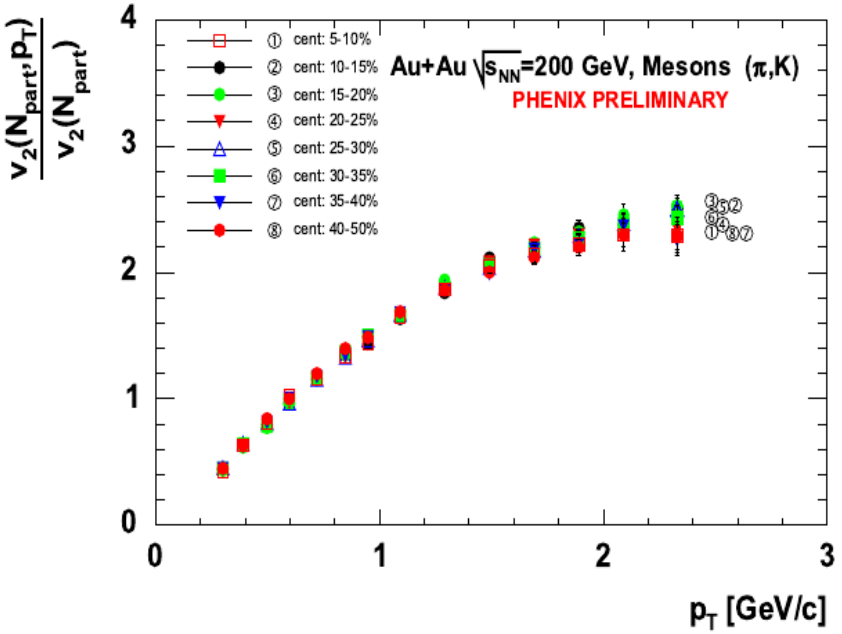




Scaling properties of azimuthal anisotropy of mesons and baryons at RHIC,

A. Taranenko, Acta Phys. Hung. A 25 (2006) 371-379

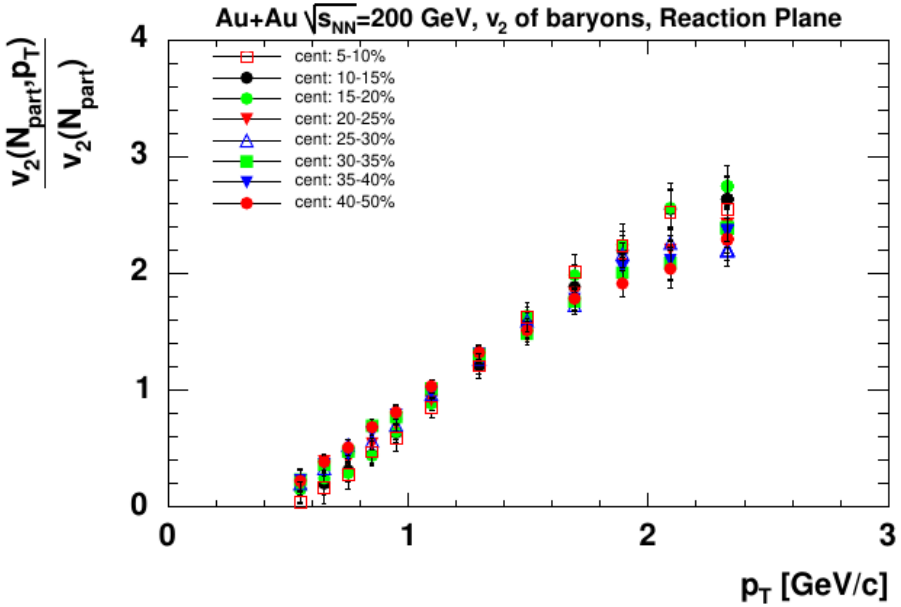
21st Winter Workshop on Nuclear dynamics, 2005, Breckenridge, USA

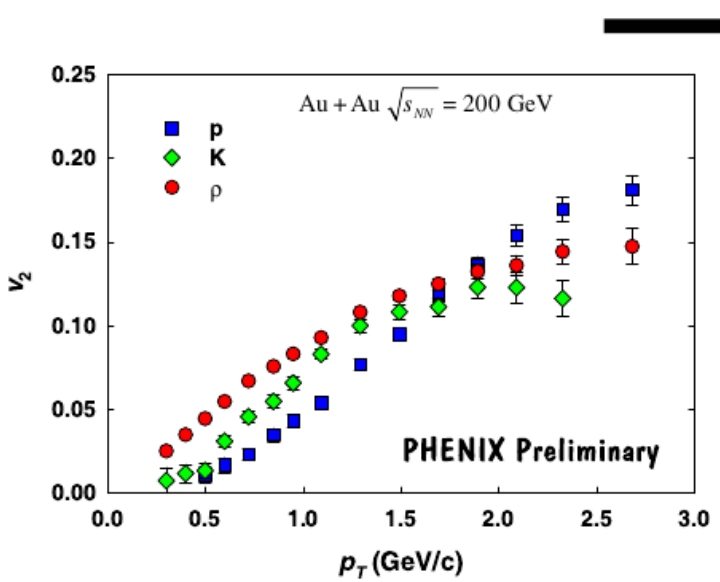


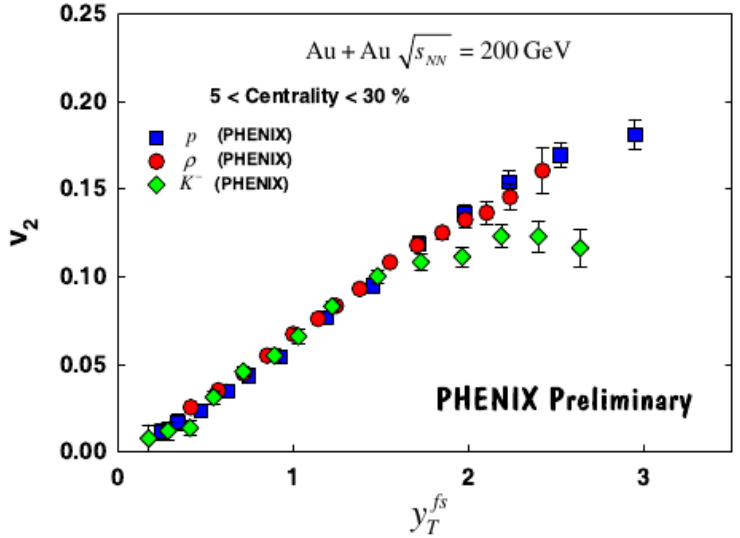
flavor scaling via substitution of the transverse rapidity [21], $y_T = \sinh^{-1}(p_T/m)$ in Eq. (2) to give

$$v_2 = k_1 y_T^2 \frac{m}{T_0}\left(1 + \frac{k_2}{k_1}\frac{T_0}{m} + \frac{k_3}{k_1}\frac{T_0^2}{m}\ldots\right), \qquad (5)$$

where, $k_1, k_2, k_3, \ldots$ are largely governed by the expansion rate. Close inspection of the leading term in Eq. 5 indicates that v_2 for different particle species should scale with $y_T^{\rm fs} = k_m \cdot y_T^2 m$. Here k_m is a mass dependent factor which is $\simeq$1 for relatively heavy particles. It is straightforward to show that hydrodynamics also predicts that







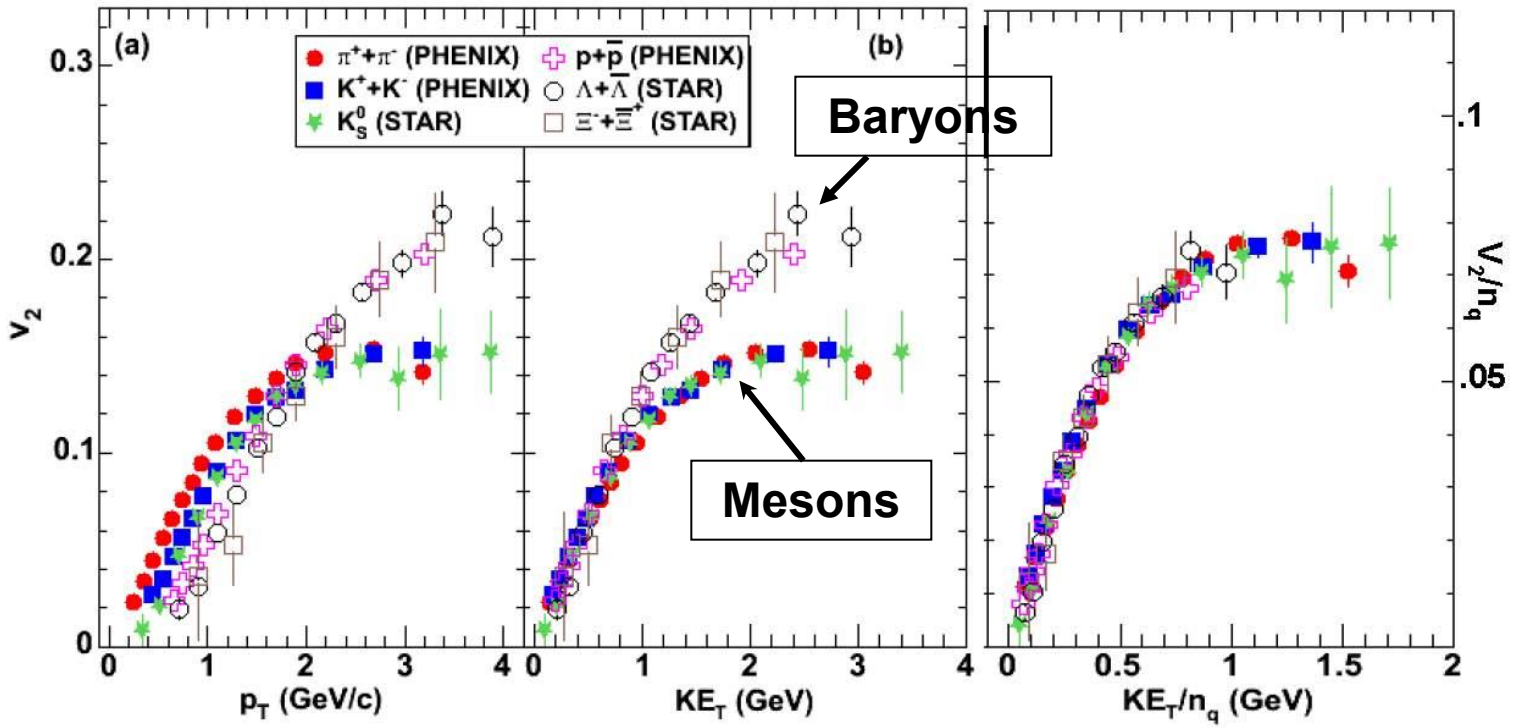
KE_T Scaling

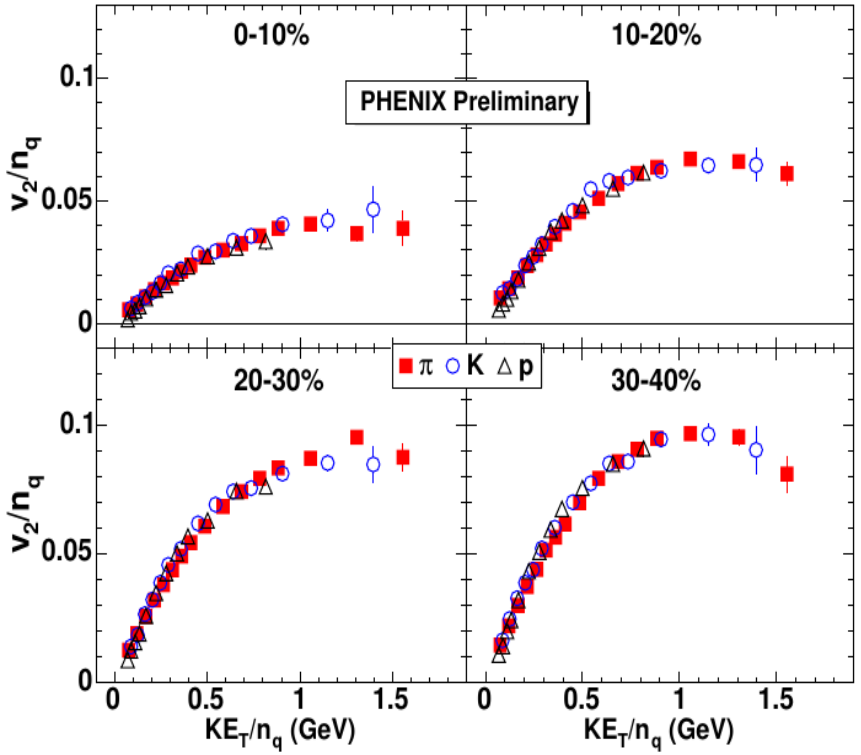
$$KE = (KE_{Therm}) + \left(KE_{col} = \frac{1}{2} m \langle u \rangle^2\right)$$

P

22nd Winter Workshop
on Nuclear Dynamics
La Jolla, California, USA
March 11–18, 2006

$KE_T = m\ (\gamma_T - 1)$



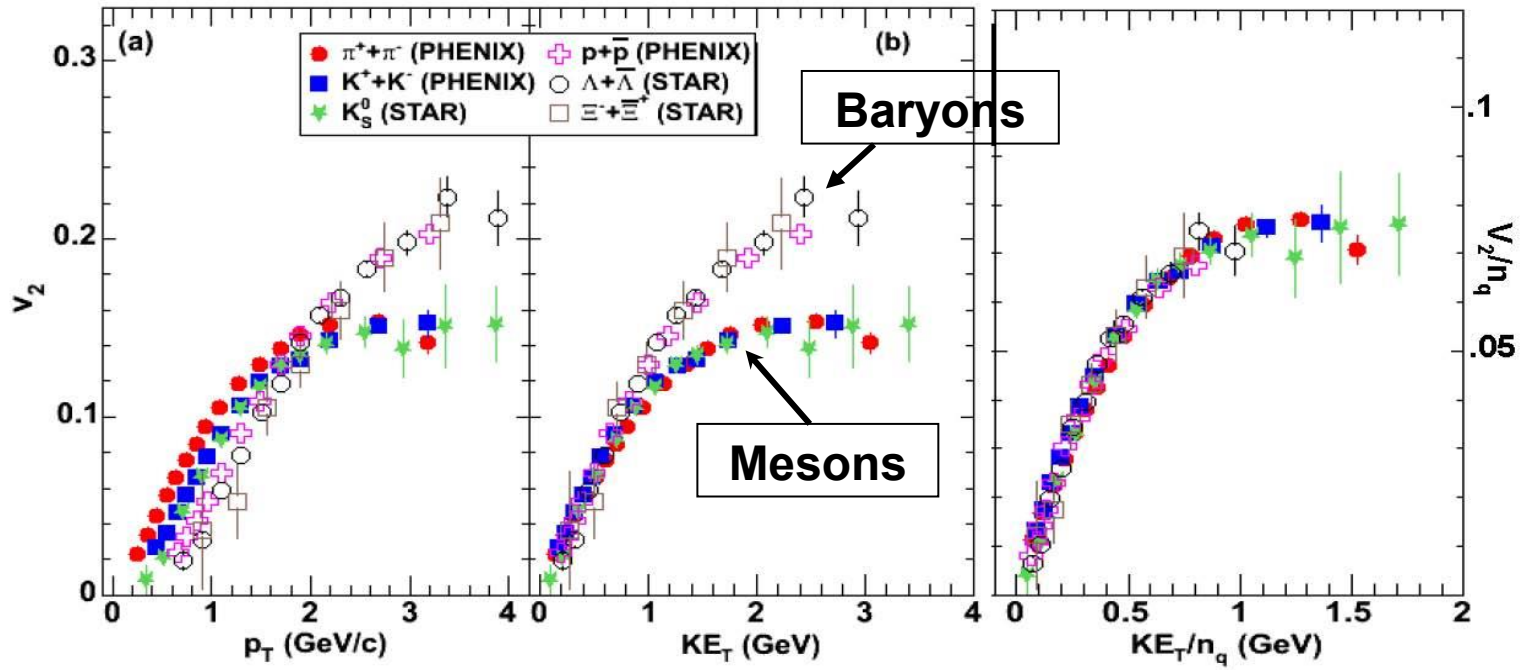


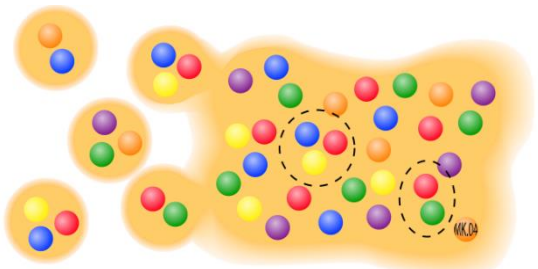
KE_T scaling validated

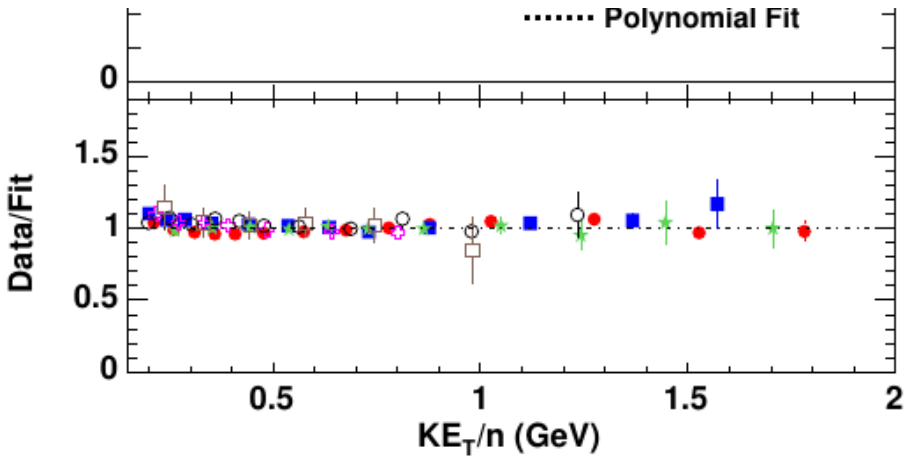
https://arxiv.org/abs/nucl-ex/0604011

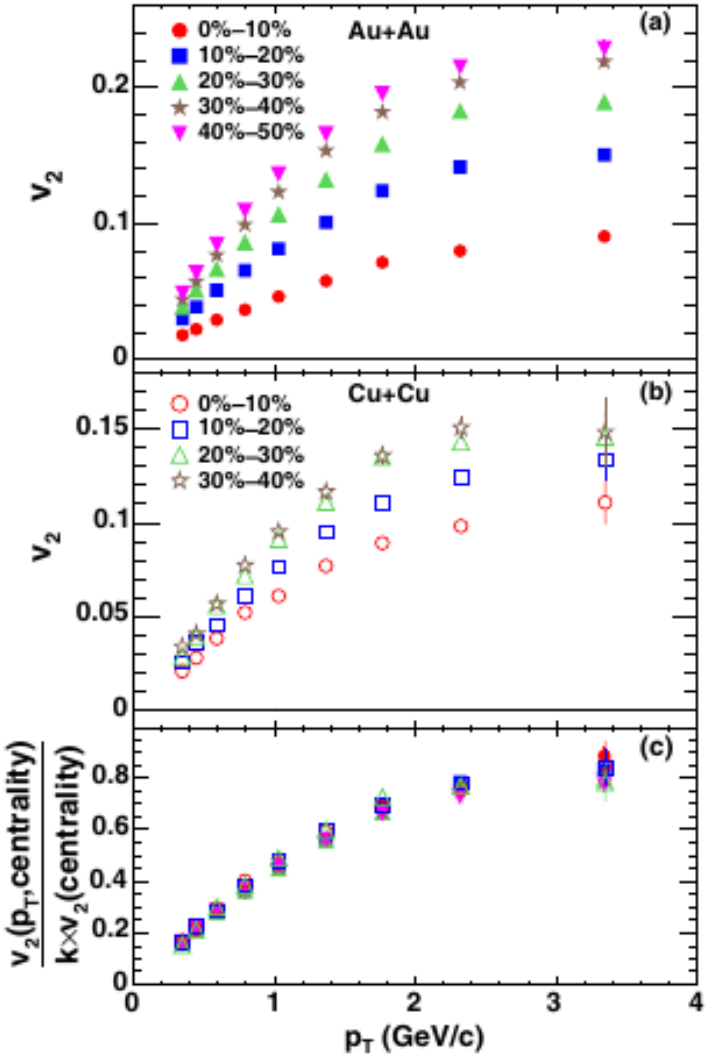
Quark Degrees of Freedom?

Scaling Properties of Azimuthal Anisotropy in Au + Au and Cu + Cu Collisions at $\sqrt{s_{NN}} = 200$ GeV

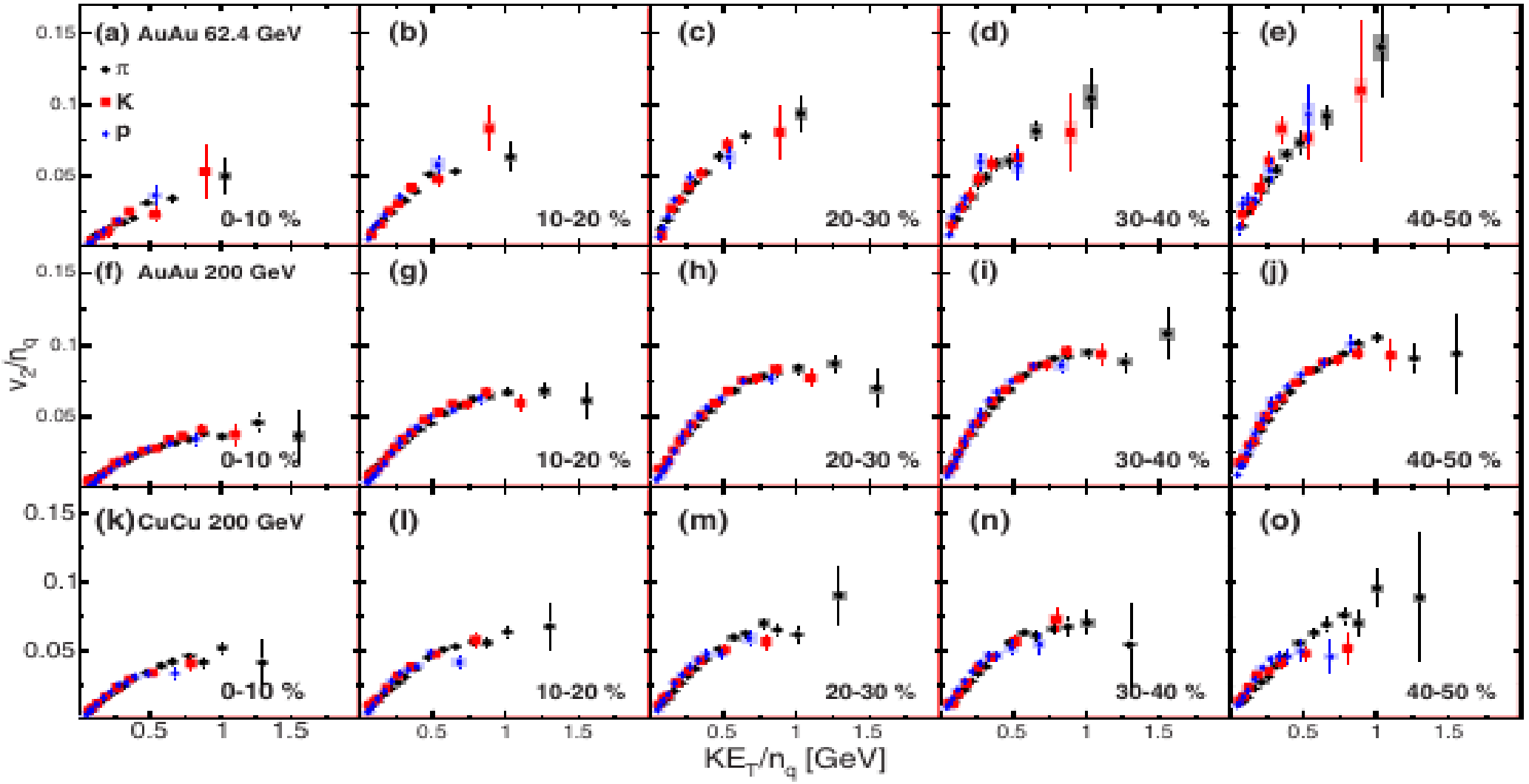








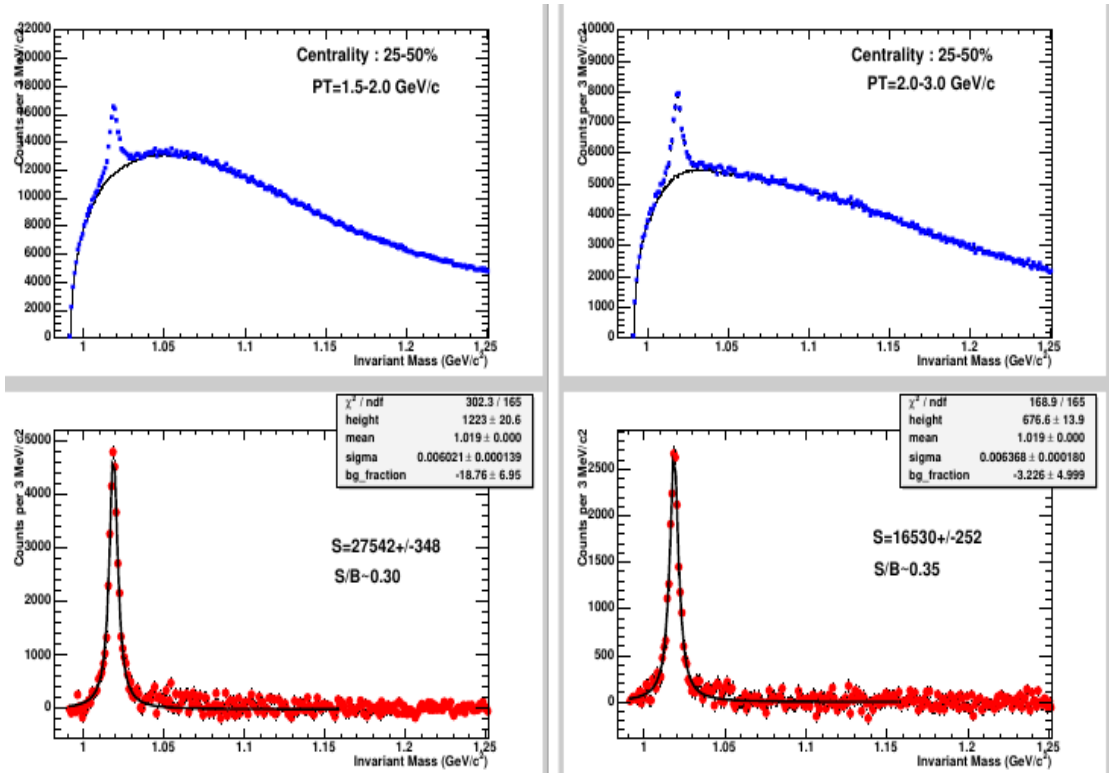
Systematic study of azimuthal anisotropy in Cu + Cu and Au + Au collisions at $\sqrt{s_{NN}} = 62.4$ and 200 GeV



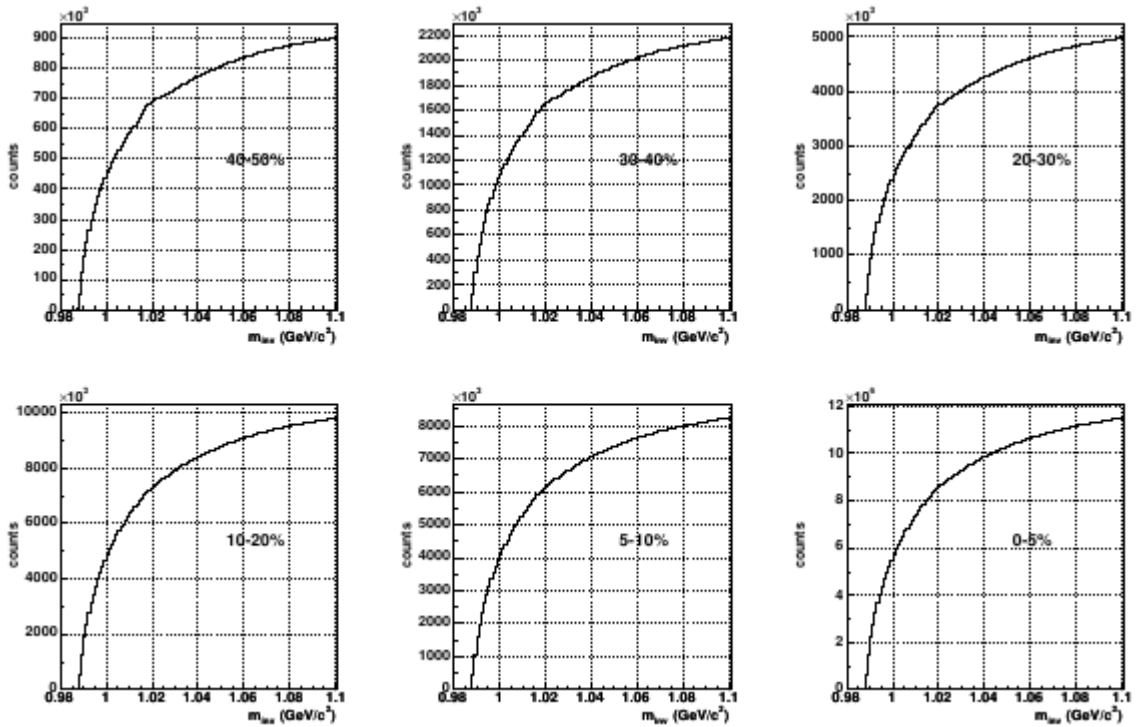
PRL 99, 052301 (2007) PHYSICAL REVIEW LETTERS week ending 3 AUGUST 2007

Elliptic Flow for ϕ Mesons and (Anti)deuterons in Au + Au Collisions at $\sqrt{s_{NN}} = 200$ GeV

PHENIX (EMC+TOF)

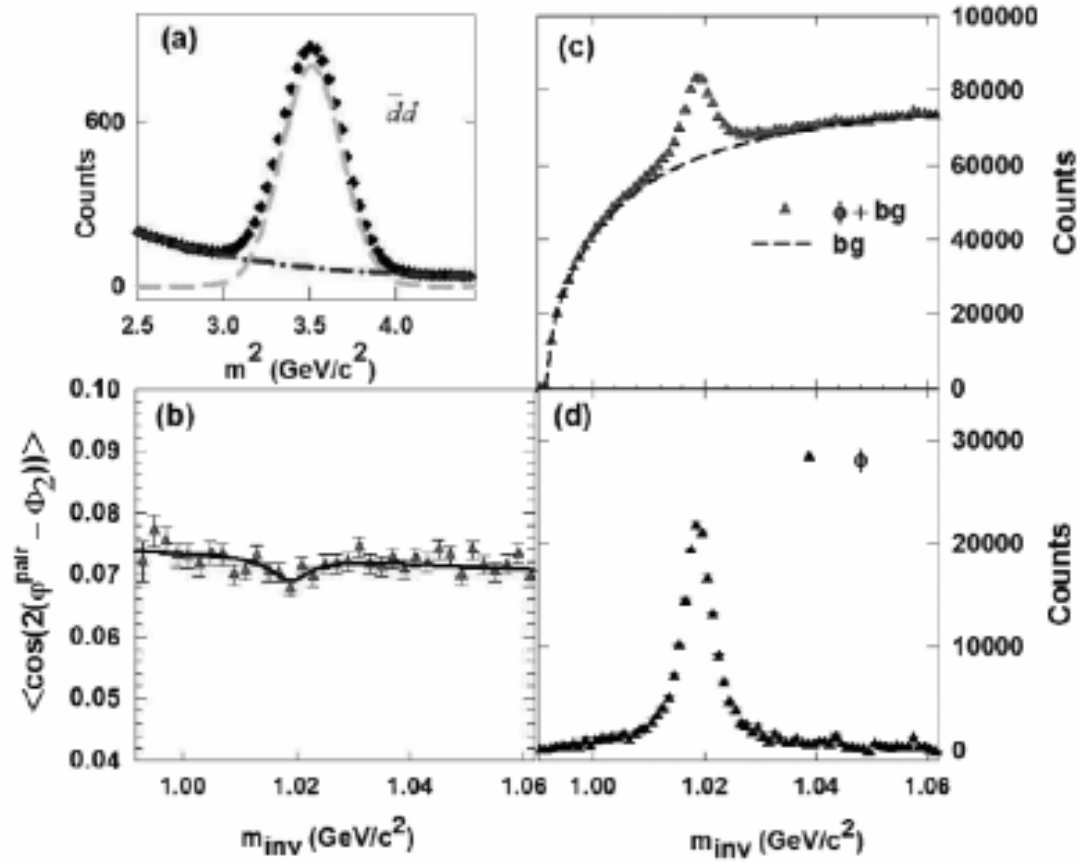


STAR (TPC)



Elliptic Flow for ϕ Mesons and (Anti)deuterons in Au + Au Collisions at $\sqrt{s_{NN}} = 200$ GeV

$$v_2^{(\bar{d})d}(p_T) = [v_2^{s+bg}(p_T) - (1 - R)v_2^{bg}(p_T)]/R, \quad (1)$$

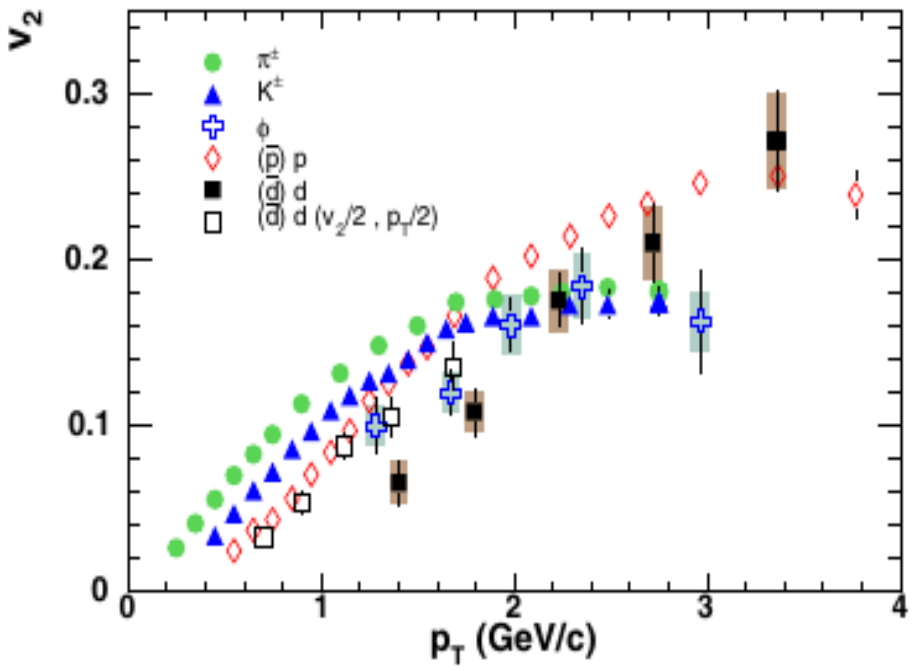


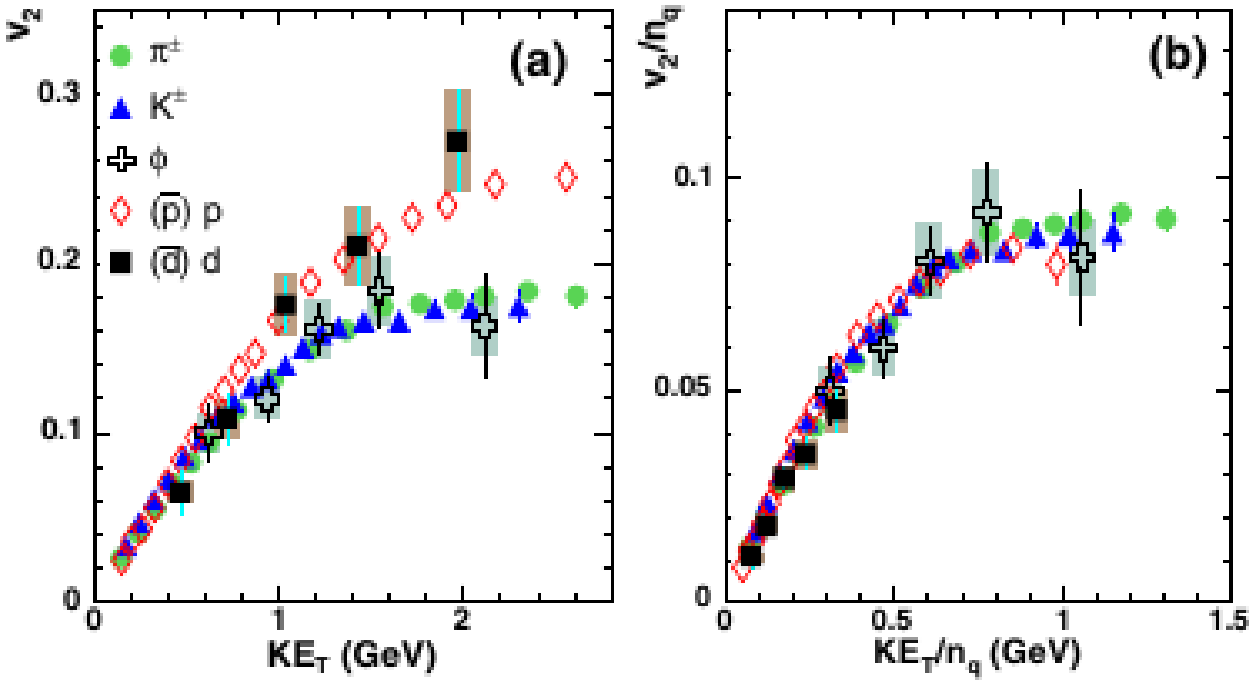
Extraction of the elliptic flow values for the ϕ meson (v_2^{ϕ}) followed the invariant mass (m_{inv}) method [38]. For each event, m_{inv}, p_T^{pair}, and φ^{pair} for each K^+K^- pair were evaluated. Then, for each p_T^{pair} bin, $v_2^{\mathrm{pair}} = \langle\cos(2(\varphi^{\mathrm{pair}} - \Phi_2))\rangle$ was evaluated as a function of m_{inv} as shown in Fig. 1(b). The value $v_2^{\phi}(p_T)$ was then obtained from $v_2^{\mathrm{pair}}(m_{\mathrm{inv}})$ via an expression similar to Eq. (1):

$$v_2^{\mathrm{pair}}(m_{\mathrm{inv}}) = v_2^{\phi} R(m_{\mathrm{inv}}) + v_2^{\mathrm{bg}}(m_{\mathrm{inv}})[1 - R(m_{\mathrm{inv}})], \quad (2)$$

where $R(m_{\mathrm{inv}}) = N_{\phi}(m_{\mathrm{inv}})/[N_{\phi}(m_{\mathrm{inv}}) + N_{\mathrm{bg}}(m_{\mathrm{inv}})]$ and $N_{\phi}(m_{\mathrm{inv}})$ and $N_{\mathrm{bg}}(m_{\mathrm{inv}})$ are distributions for the ϕ meson and the combinatoric background, respectively, $N_{\phi}(m_{\mathrm{inv}})$ is obtained from the distribution $N_{\mathrm{pair}}(m_{\mathrm{inv}})$ of K^+K^- pairs from the same event (foreground); $N_{\mathrm{bg}}(m_{\mathrm{inv}})$ is the distribution of pairs obtained from different events with similar centrality, vertex, and event plane orientation [39].

Elliptic Flow for ϕ Mesons and (Anti)deuterons in Au + Au Collisions at $\sqrt{s_{NN}} = 200$ GeV





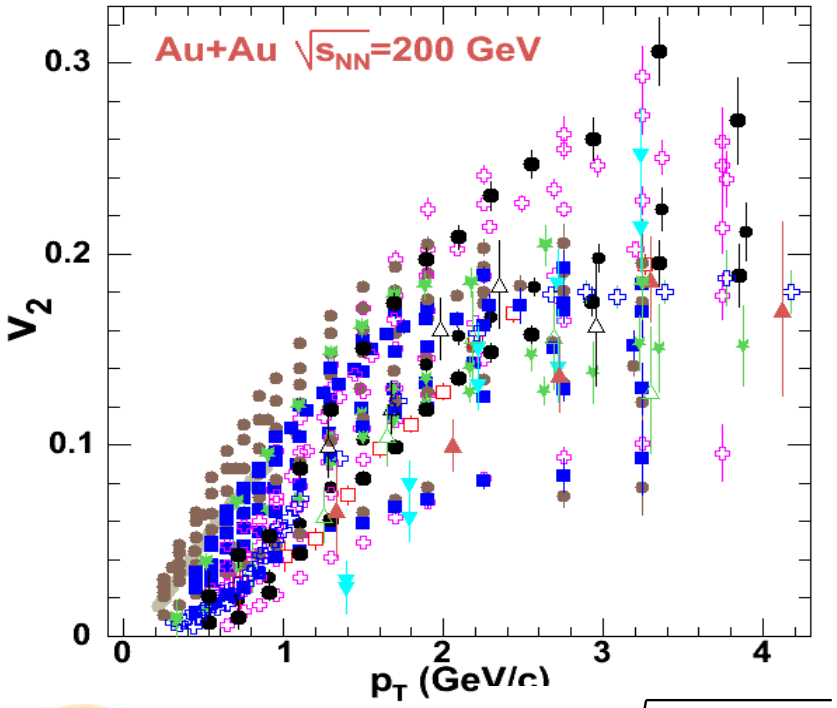
Gordon Research Conference 2006 (New London, USA, 2006 r.)

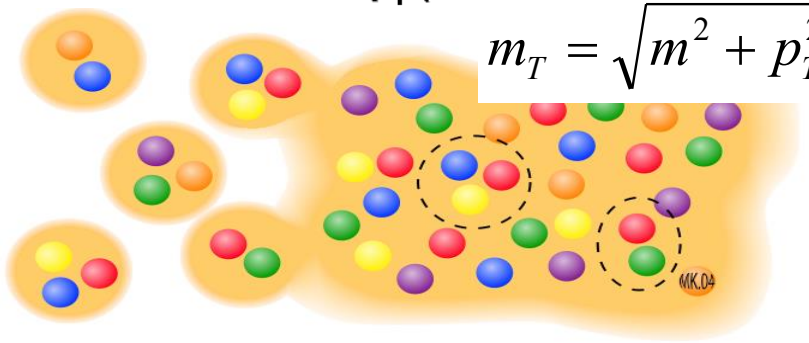
Quark Matter 2006 (Shanghai, China, 2006 r.),

What do elliptic flow measurements tell us about the matter created in the little bang at RHIC?, R.A. Lacey, A. Taranenko, PoS CFRNC2006 (2006) 021
PHENIX studies of the scaling properties of elliptic flow at RHIC, A. Taranenko, J. Phys. G 34 (2007) S1069-1072

Anisotropic Flow at RHIC – scaling relations

PHENIX studies of the scaling properties of elliptic flow at RHIC,
A. Taranenko, J. Phys. G 34 (2007) S1069-1072





$$m_T = \sqrt{m^2 + p_T^2}$$

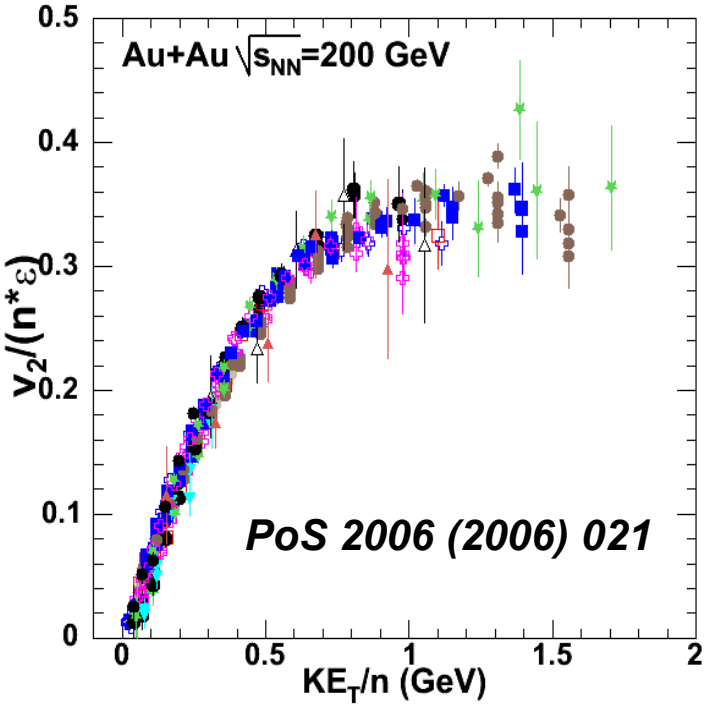
PHENIX (Phys.Rev.Lett.91, Preliminary: QM05, GRC 06)

- $\pi^+ + \pi^-$: min.bias, 0-10%,10-20%,20-30%,30-40%,40-50%,20-60%
- $K^+ + K^-$: min.bias, 0-10%,10-20%,20-30%,30-40%,40-50%,20-60%
- $p + \bar{p}$: min.bias, 0-10%,10-20%,20-30%,30-40%,40-50%,20-60%
- d: min.bias, 10-50%
- ϕ: 20-60%

STAR (Phys. Rev. Lett. 92,Phys. Rev. C 72 (2005), Preliminary QM05, SQM06)

- $\pi^+ + \pi^-$: min.bias
- K^0_S: min.bias, 5-30%,30-70%
- $p + \bar{p}$: min.bias
- $\Lambda + \bar{\Lambda}$: min.bias, 5-30%,30-70%
- $\Xi + \bar{\Xi}$: min.bias
- $\Omega + \bar{\Omega}$: min.bias

$$KE_T = m(\gamma_T - 1) = m_T - m$$

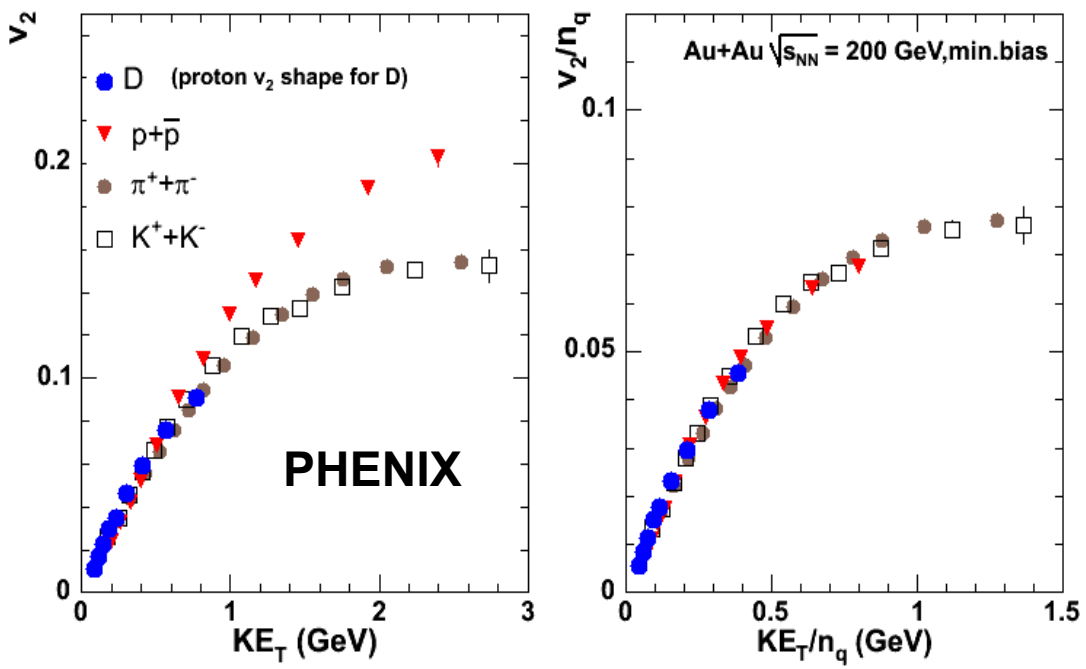


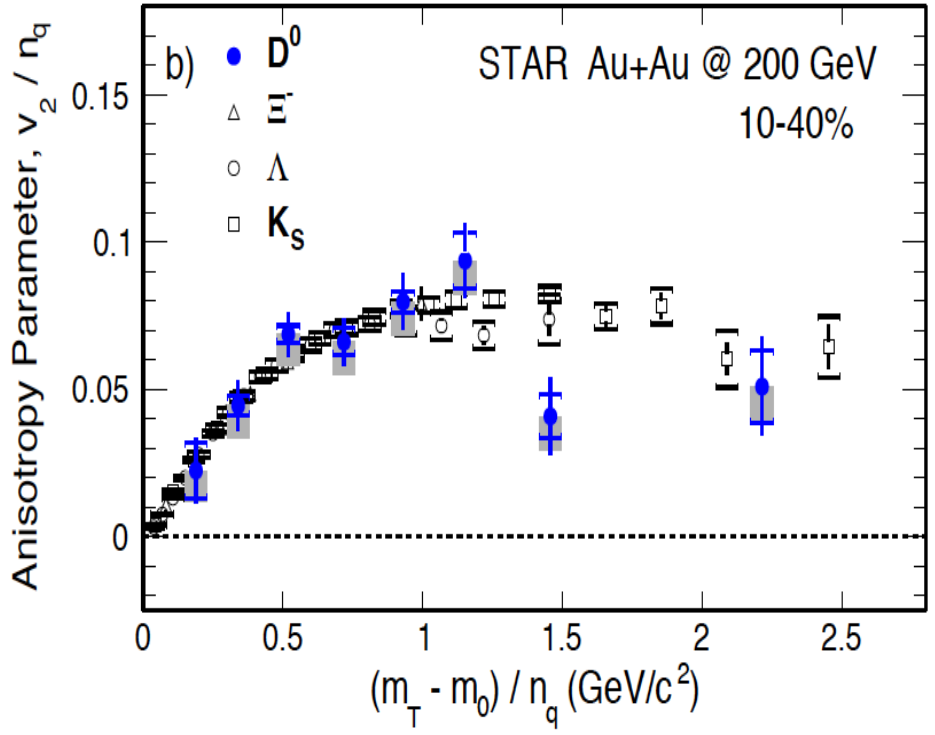
n=2 for mesons and n=3 for baryons

Elliptic flow of D meson in 2006-2017

PHENIX studies of the scaling properties of elliptic flow at RHIC,
A. Taranenko, J. Phys. G 34 (2007) S1069-1072

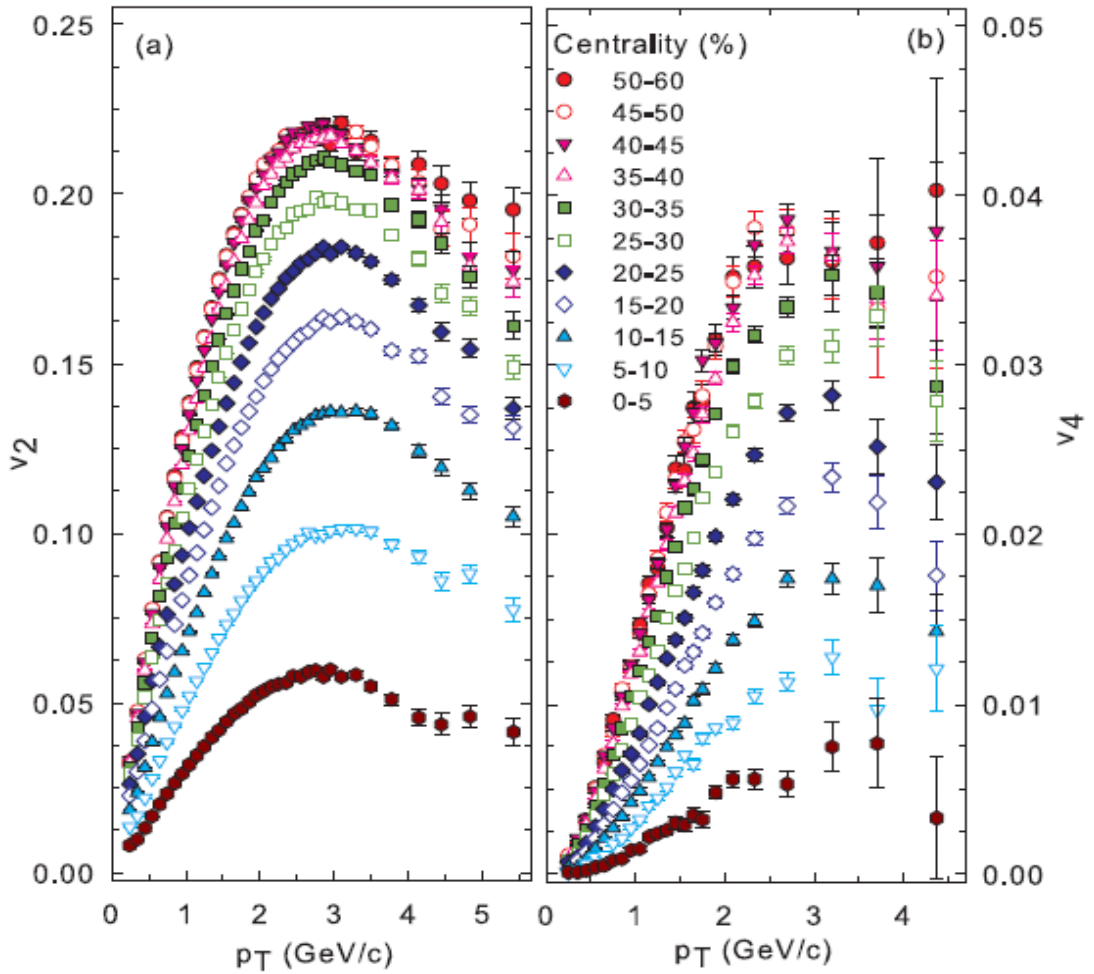
STAR, PRL118 (2017) 212301



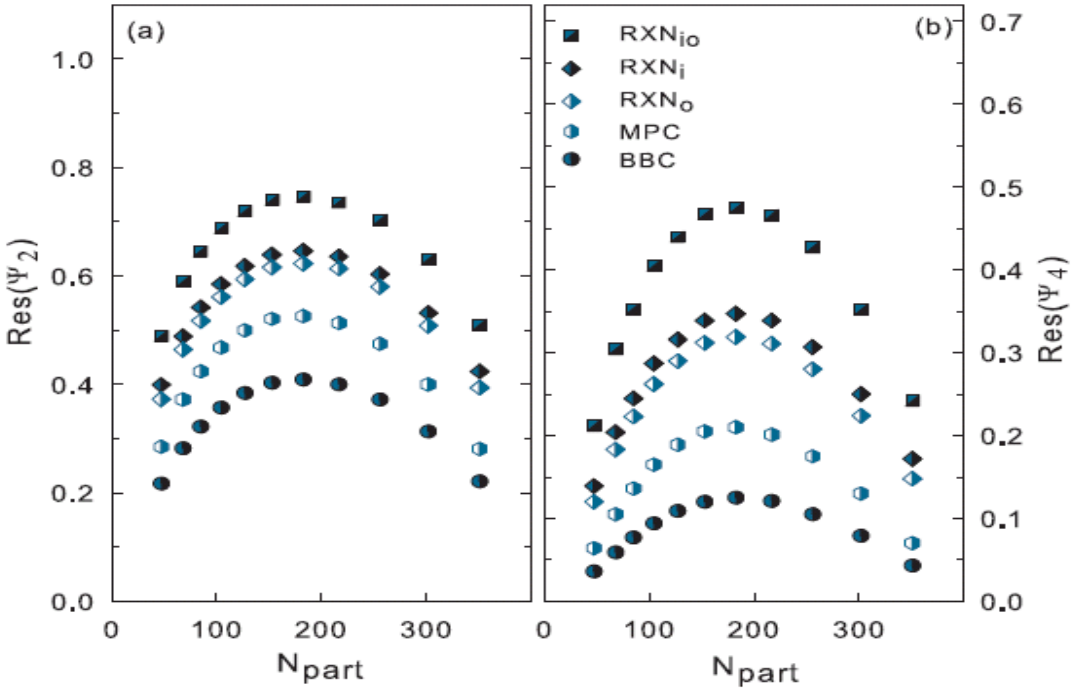


The D meson not only flows, it scales over the measured range

Elliptic and Hexadecapole Flow of Charged Hadrons in Au + Au Collisions at $\sqrt{s_{NN}} = 200$ GeV



$$v_{2k}^{i} = \frac{\langle \cos(2k(\phi_p - \Phi_2^i)) \rangle}{\mathrm{Res}(\Psi_{2k}^i)} \quad k = 1, 2$$

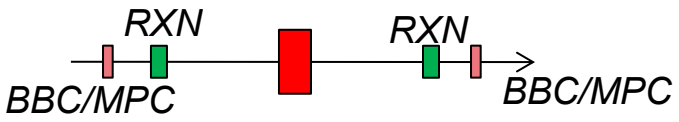


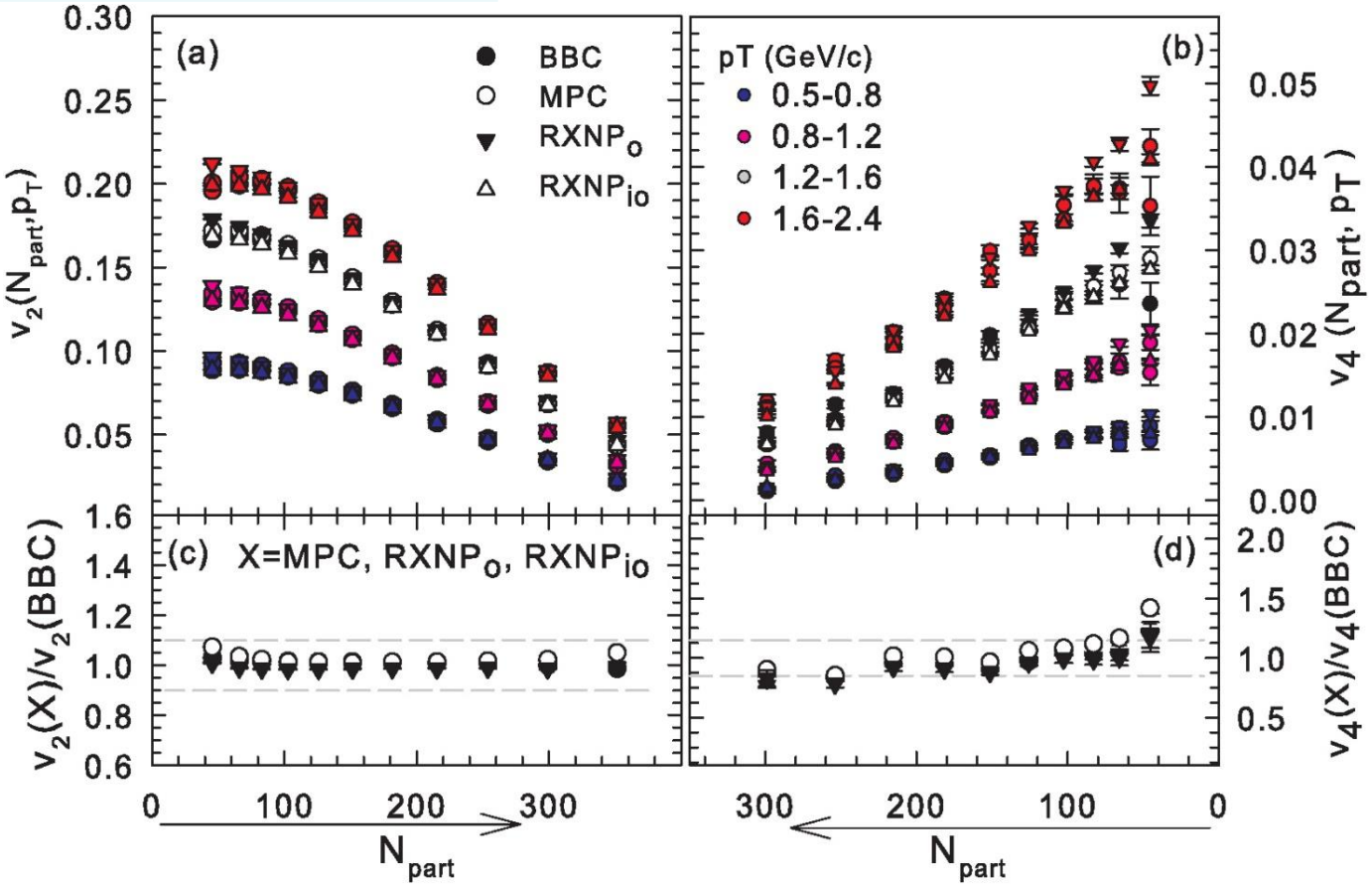
$$i = RXN_{io},\ l = MPC_N,\ m = BBC_S$$

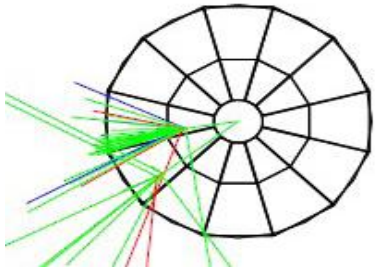
$$\mathrm{Res}(\Psi_{2k}^i) = \sqrt{\frac{\langle \cos(2k(\Phi_2^i - \Phi_2^l)) \rangle \langle \cos(2k(\Phi_2^i - \Phi_2^m)) \rangle}{\langle \cos(2k(\Phi_2^l - \Phi_2^m)) \rangle}} \quad (2)$$

High precision double differential measurements

PHENIX Data Precision







New RXN detector

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

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

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

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

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

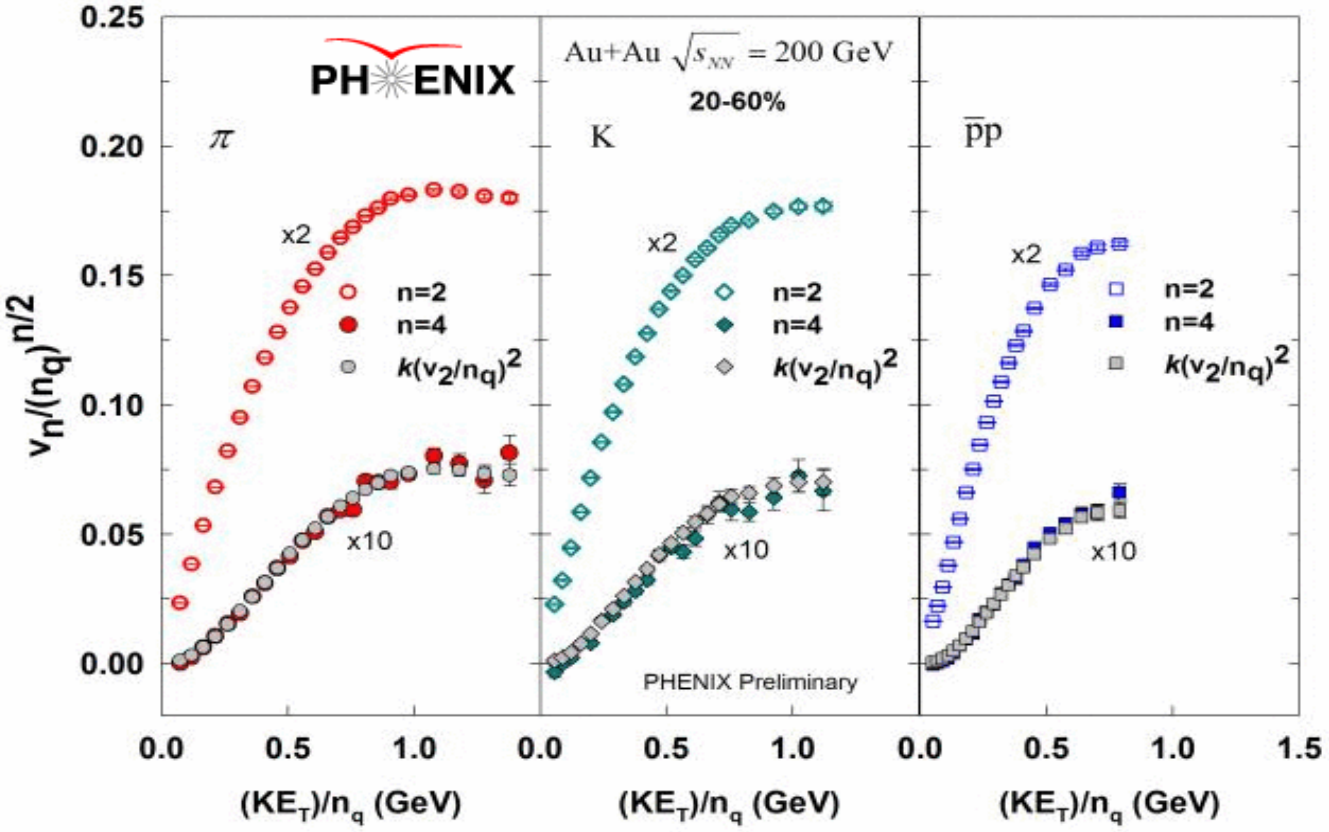
Event planes

➢ ***No evidence for significant η-dependent non-flow contributions***

Results from different methods should Not be used as a measure of systematic error!

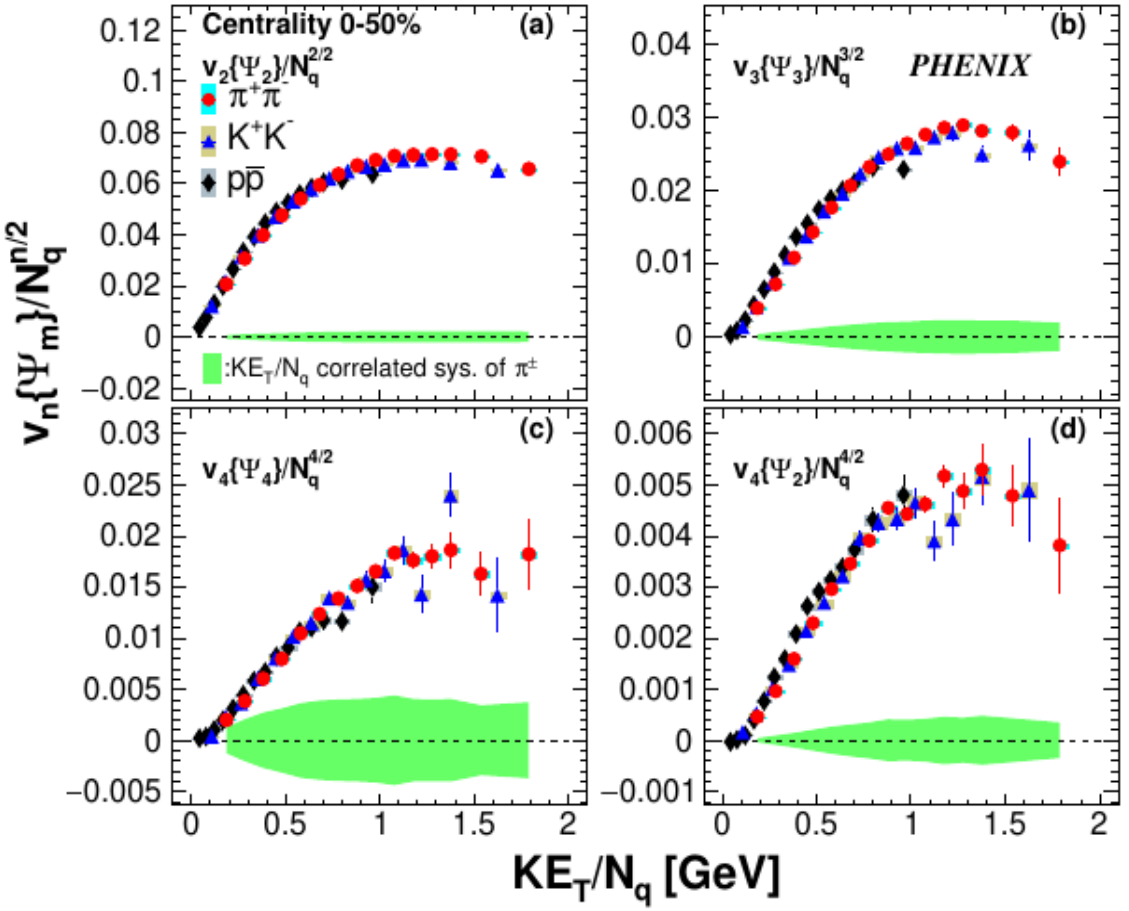
$v_4/(v_2)^2$ ratio same for different particle species

Beam Energy Dependence of Azimuthal Anisotropy at RHIC-PHENIX, A. Taranenko, Phys. Atom. Nucl. 75 (2012) 550-555

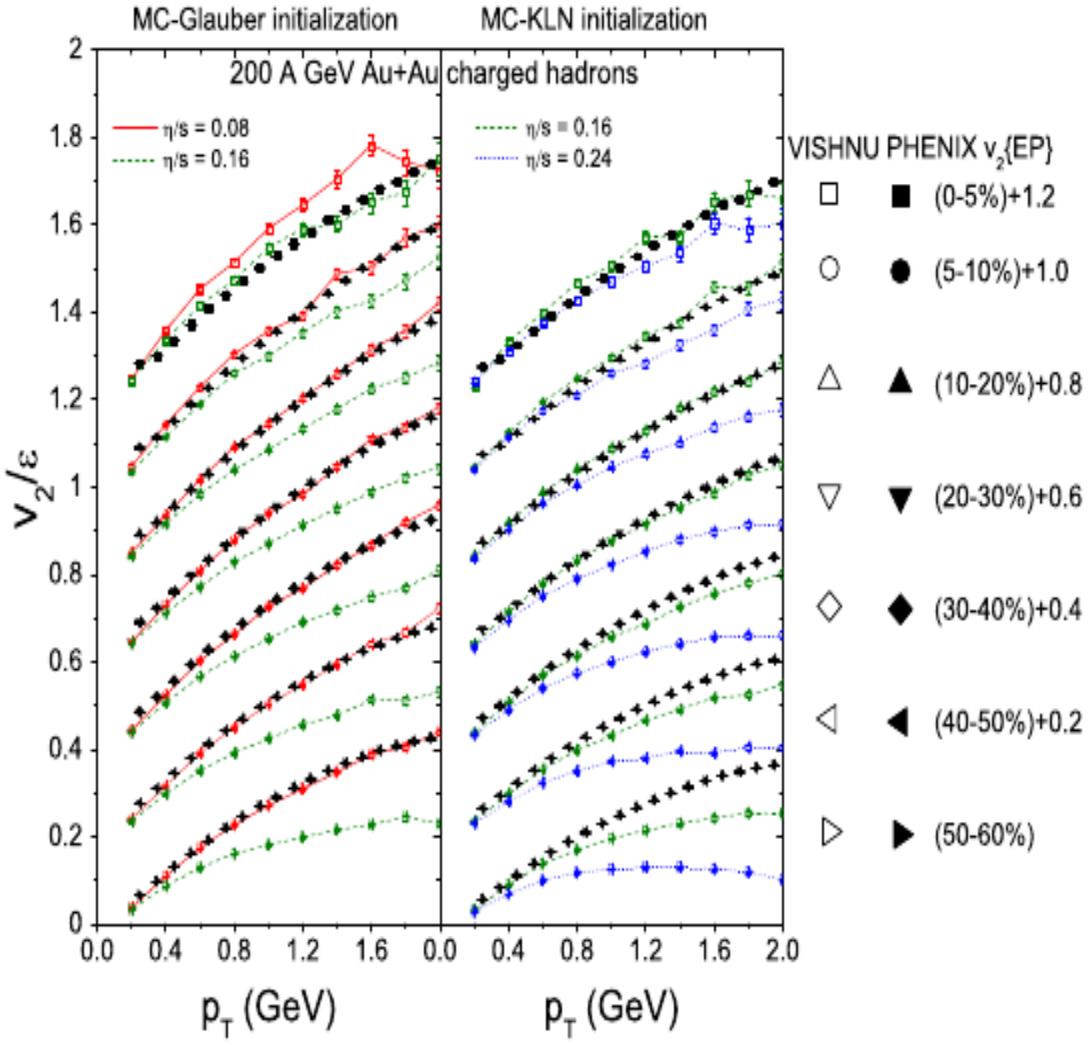


$V_4 = k(v_2)^2$ where k is the same for different particle species

Phys. Rev. C 93 (2016) 5, 051902

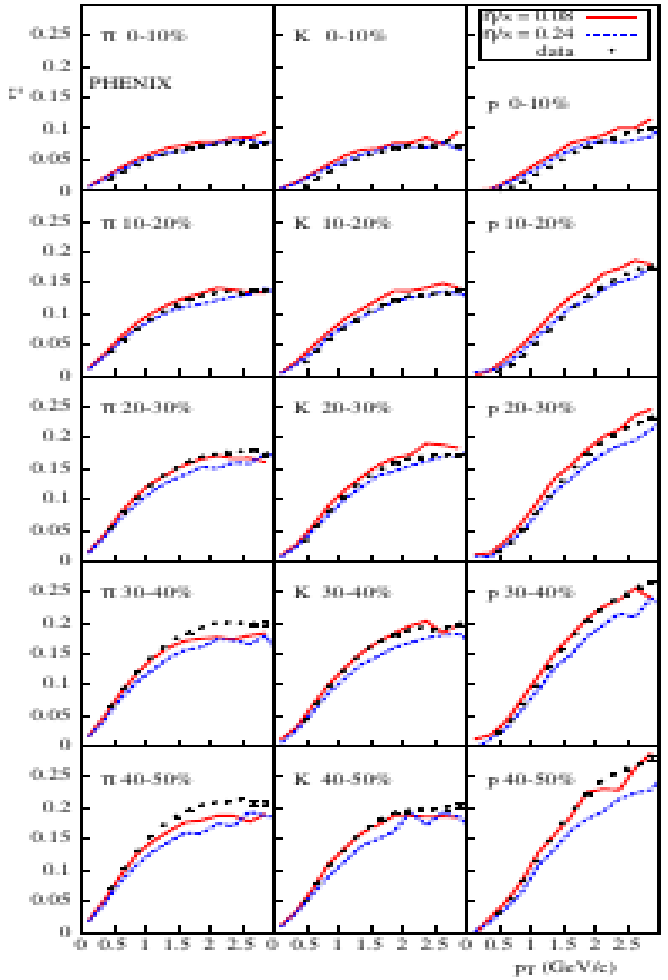


PHENIX ELLIPTIC FLOW DATA vs MODELS



Huichao Song et al. Phys.Rev.C 83 (2011) 054910

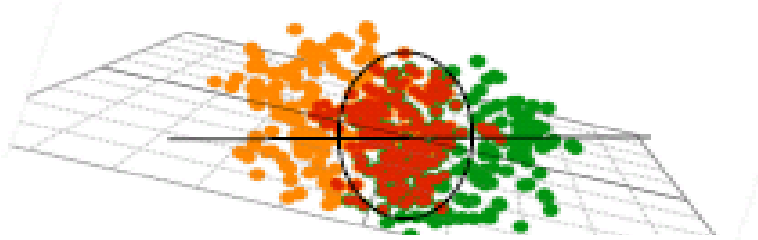
Hadron spectra and elliptic flow for 200 A GeV Au+Au collisions from viscous hydrodynamics coupled to a Boltzmann cascade

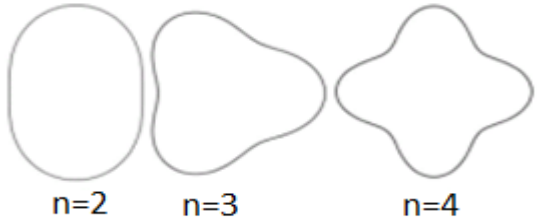


Mahbobeh Jafarpour at. Al Phys.Rev.C 113 (2026) 1, 014910

Disentangling initial-state and evolution effects in heavy-ion collisions using EPOS and PHSD

Anisotropic Flow at RHIC-LHC



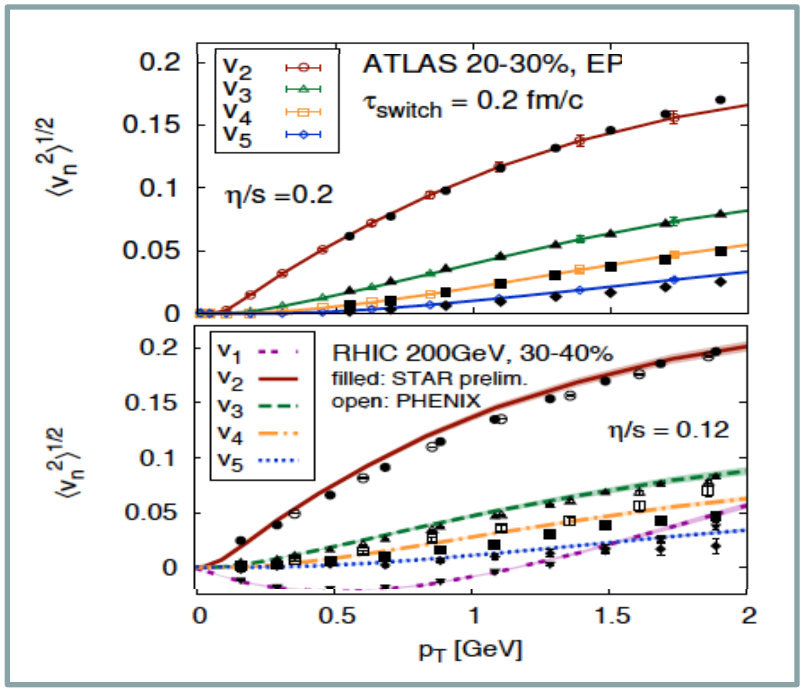


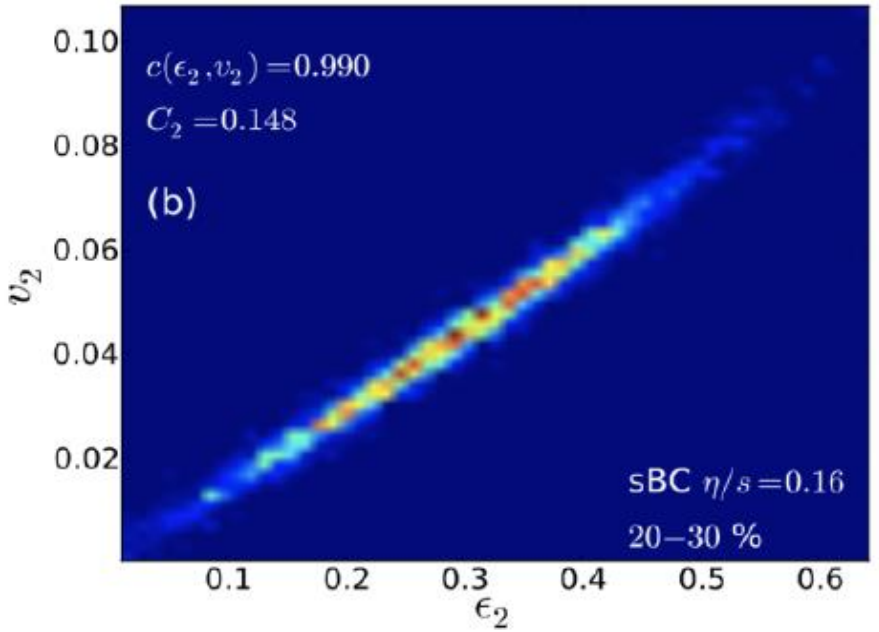
$$\epsilon_n = \sqrt{\frac{\langle r^n \cos n\phi \rangle + \langle r^n \sin n\phi \rangle}{\langle r^n \rangle}}$$

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

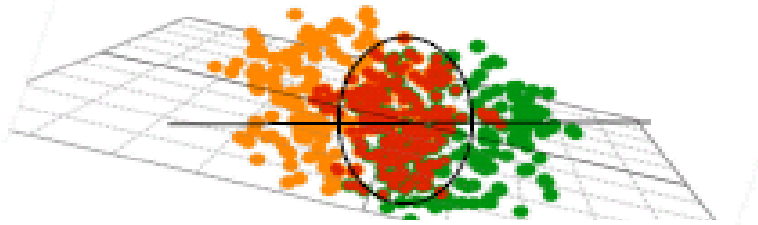
Initial eccentricity (and its attendant fluctuations) ε_n drive momentum anisotropy v_n with specific viscous modulation

Gale, Jeon, et al., Phys. Rev. Lett. 110, 012302

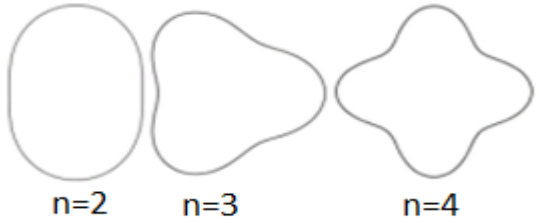




Anisotropic Flow is acoustic



$$\epsilon_n = \sqrt{\frac{\langle r^n \cos n\phi \rangle + \langle r^n \sin n\phi \rangle}{\langle r^n \rangle}}$$



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

$$k = n / \bar{R}$$

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

PRC 84, 034908 (2011)
P. Staig and E. Shuryak.

) Beam energy dependence of the viscous damping of anisotropic flow in relativistic heavy ion collisions, R.A. Lacey, A. Taranenko, Phys. Rev. Lett. 112 (2014) 8, 082302

Acoustic viscous modulation of v_n

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

n² dependence

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

v_n is related to v_2

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

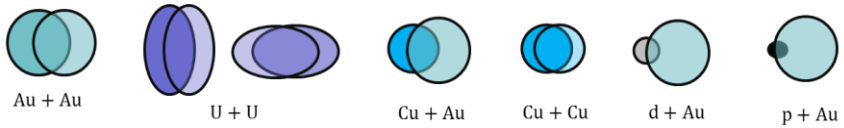
System size dependence

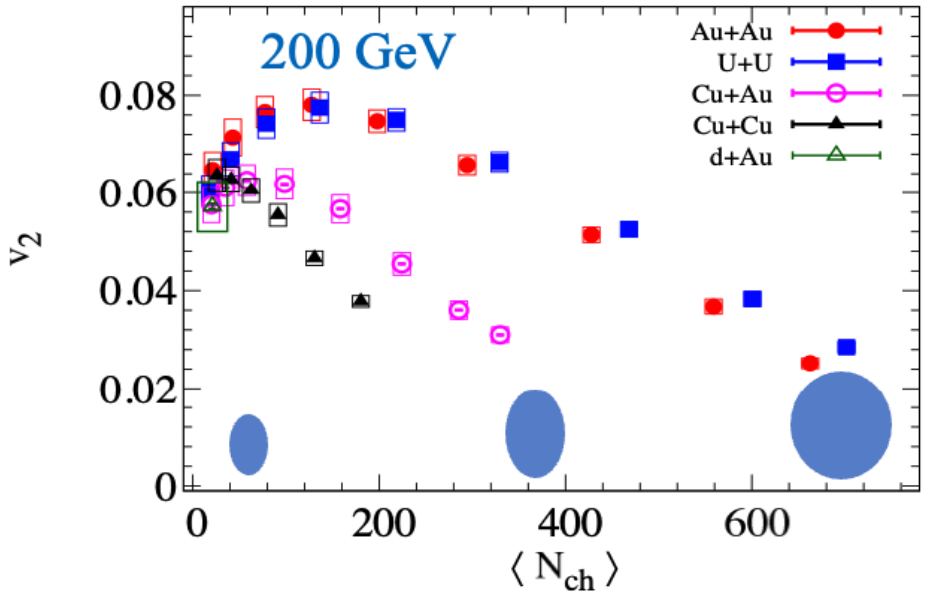
$$\ln\left(\frac{v_n}{\varepsilon_n}\right) \propto \frac{-\beta''}{\bar{R}}$$

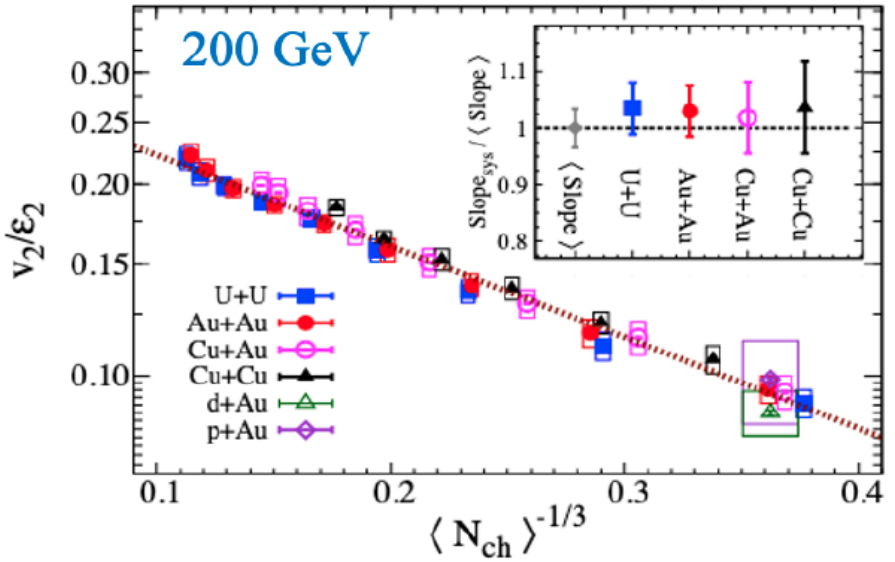
- **From macroscopic entropy considerations** $S \sim (RT)^3 \propto \frac{dN}{d\eta}$

$$ln\left(\frac{v_n}{\epsilon_n}\right) \propto A\,\frac{\eta}{s}\left(\frac{dN}{d\eta}\right)^{\frac{-1}{3}}$$

$$v_2 \propto k\,\varepsilon_2\,\langle N_{Ch}\rangle^{-1/3}$$

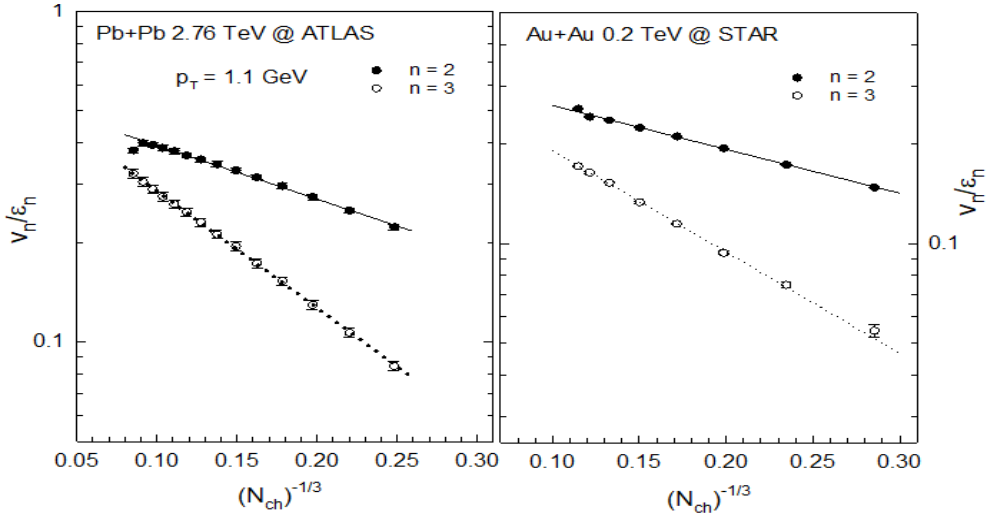


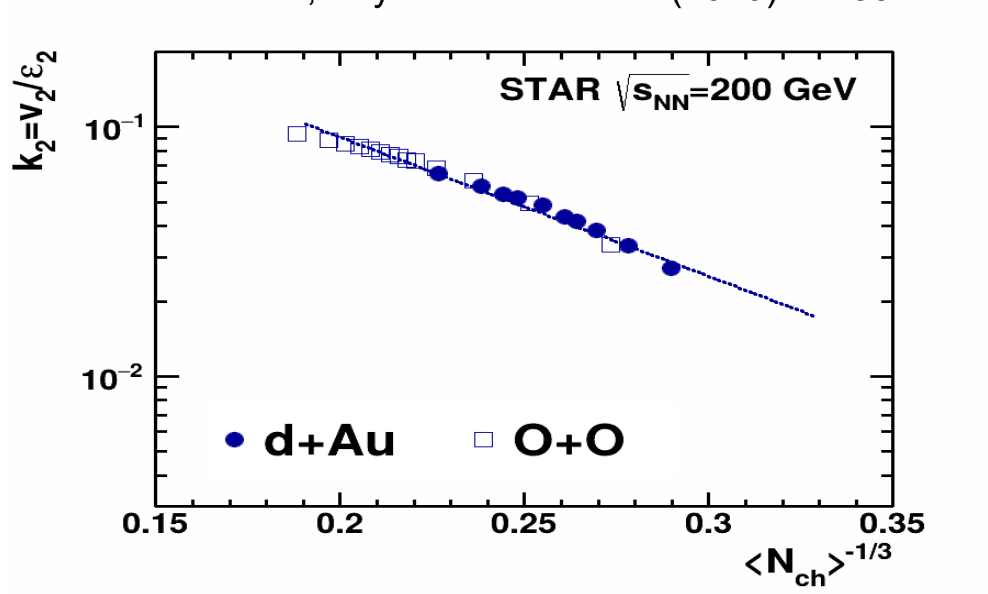




STAR, Phys. Rev. Lett. 122 (2019) 172301

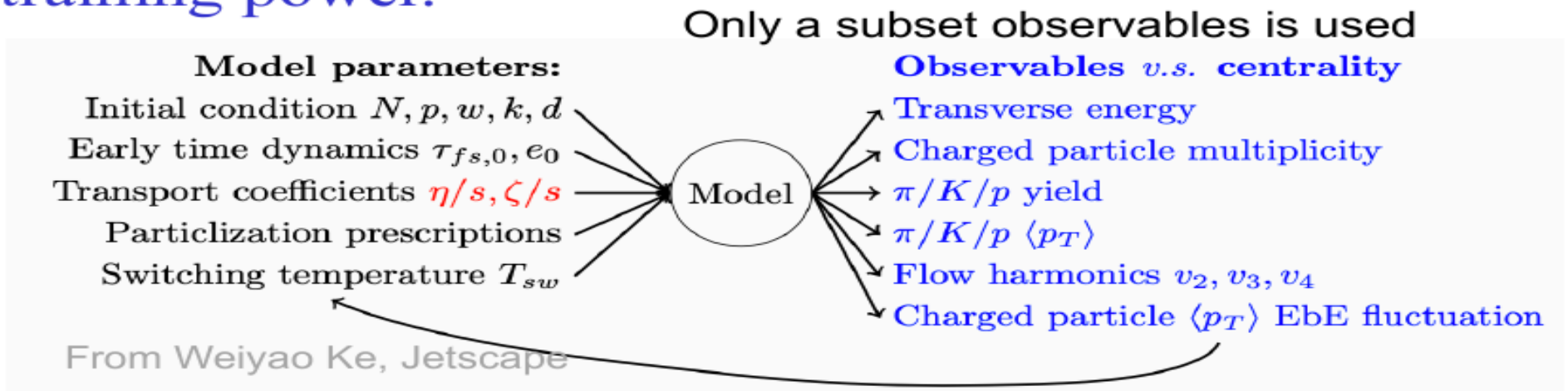
R. Lacey Phys. Rev. C **98**, 031901(R), 2018



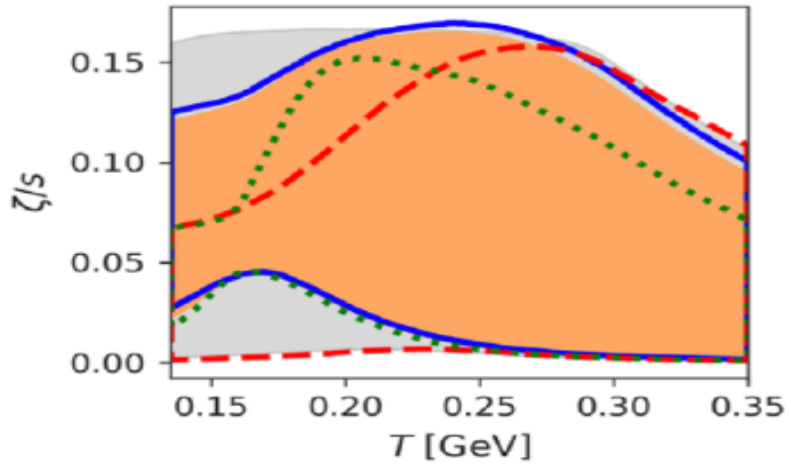


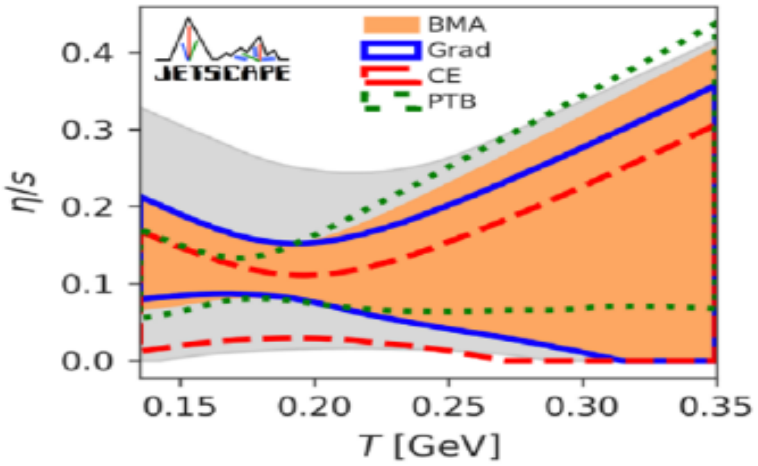
State-of-the-art modeling of HI collisions

- Data-model comparison via Bayesian inference to optimize constraining power.



- Detailed temperature dependence of viscosity!





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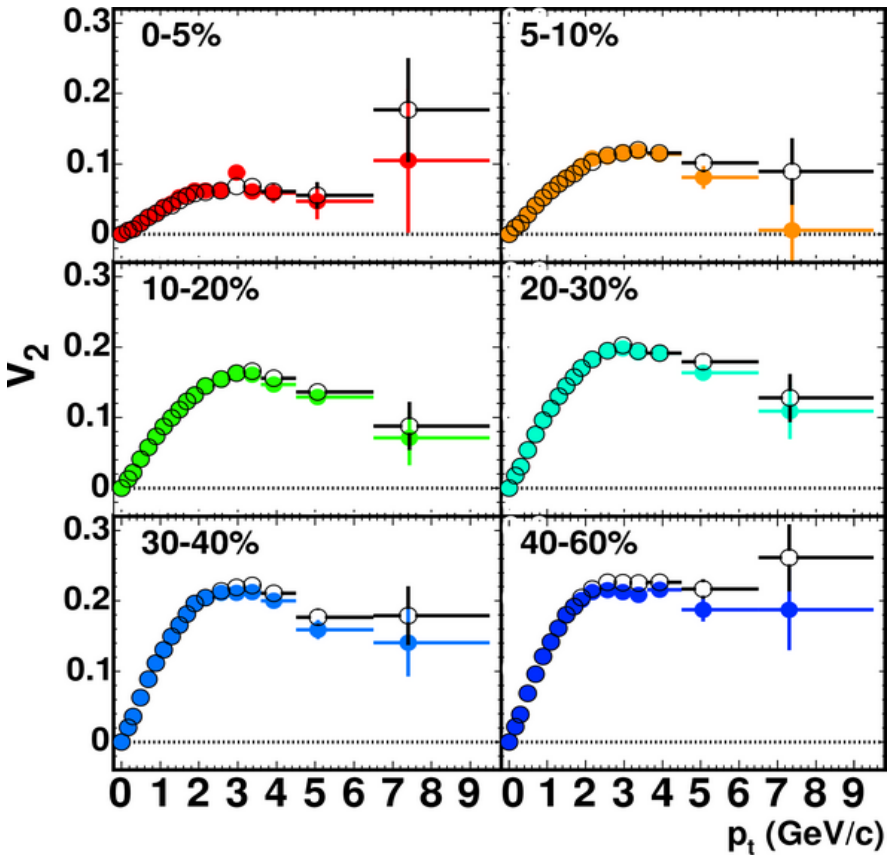
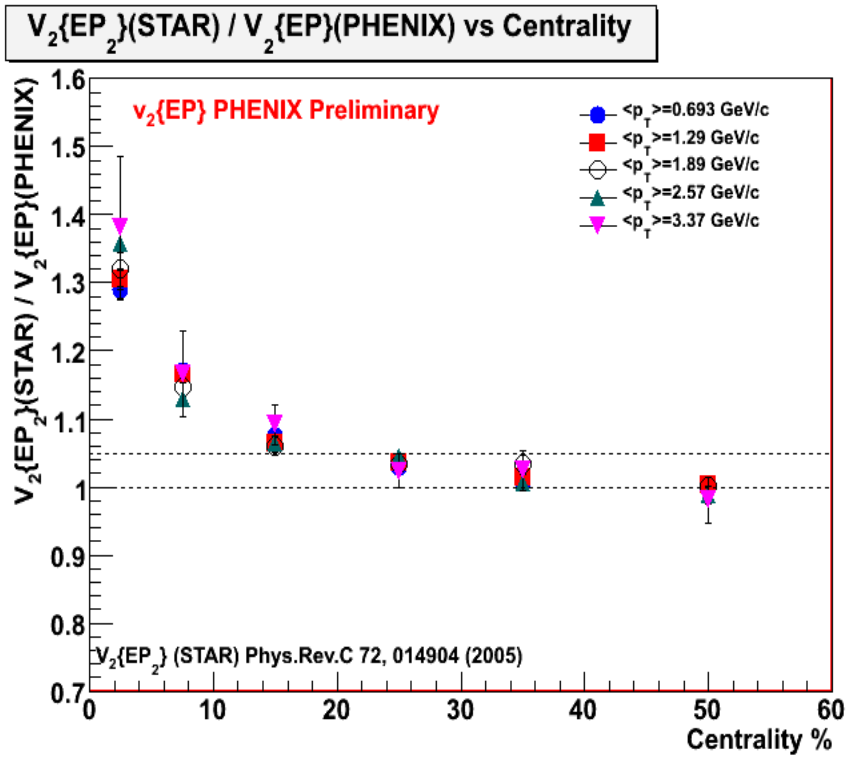
Trjactum PRL.126.202301

Major uncertainty: initial condition and pre-hydro phase

Elliptic Flow at RHIC $v_2(p_T$, centrality): STAR vs PHENIX

Phys.Rev. C72(2005) 14904



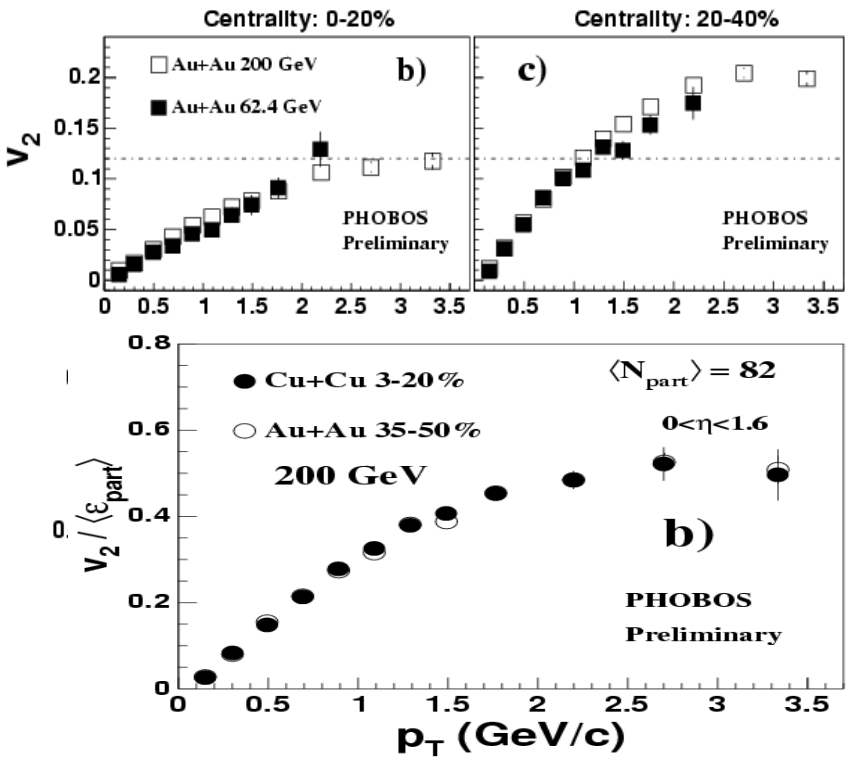




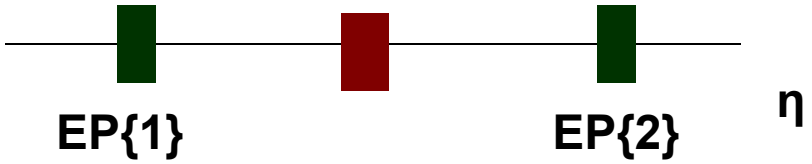
2005: The only published STAR data for inclusive charged hadrons from Au+Au at 200 GeV (in the last 20 years !!!)

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

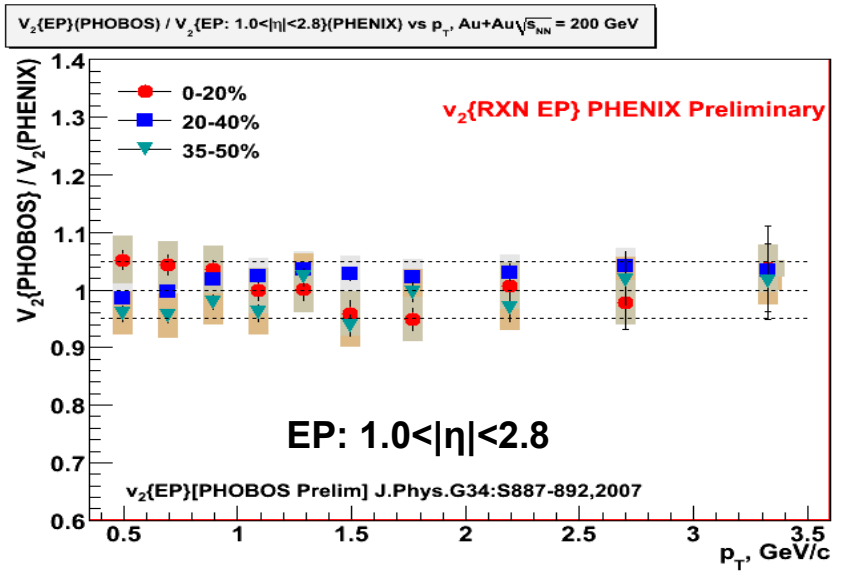
Elliptic Flow at RHIC $v_2(p_T$, centrality): PHOBOS/PHENIX

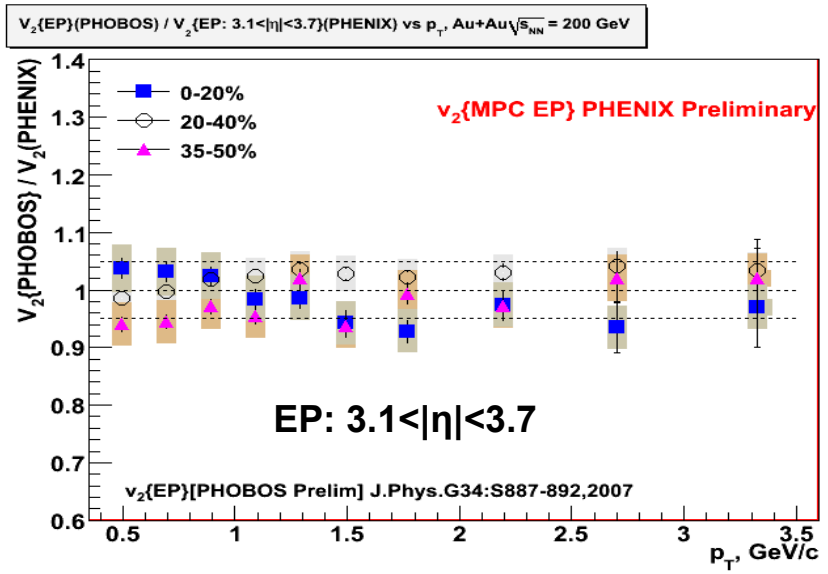


from PHOBOS QM06 proc. J. Phys. G34 S887 (2007)



PHOBOS EP: 2.05<|η|<3.2



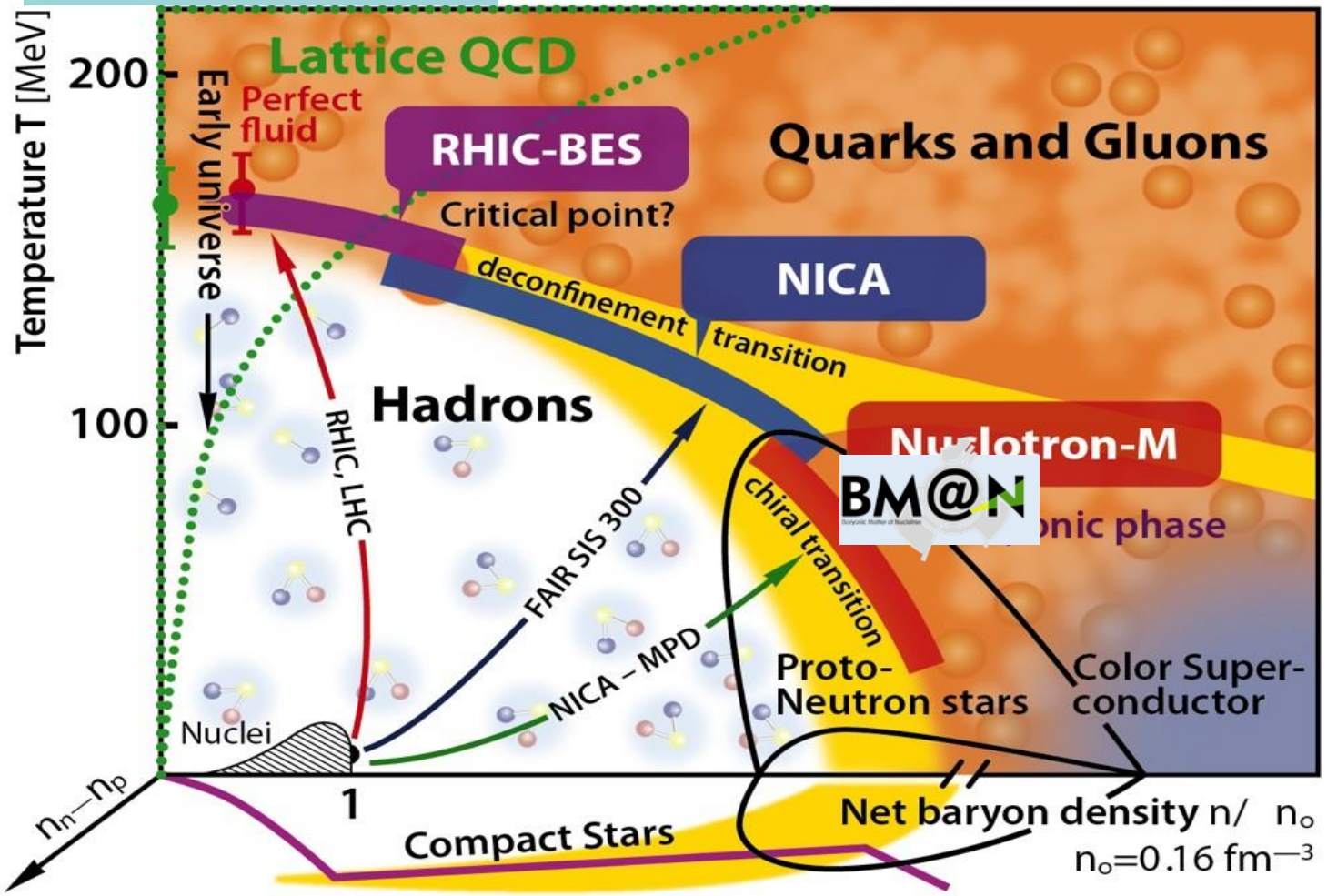


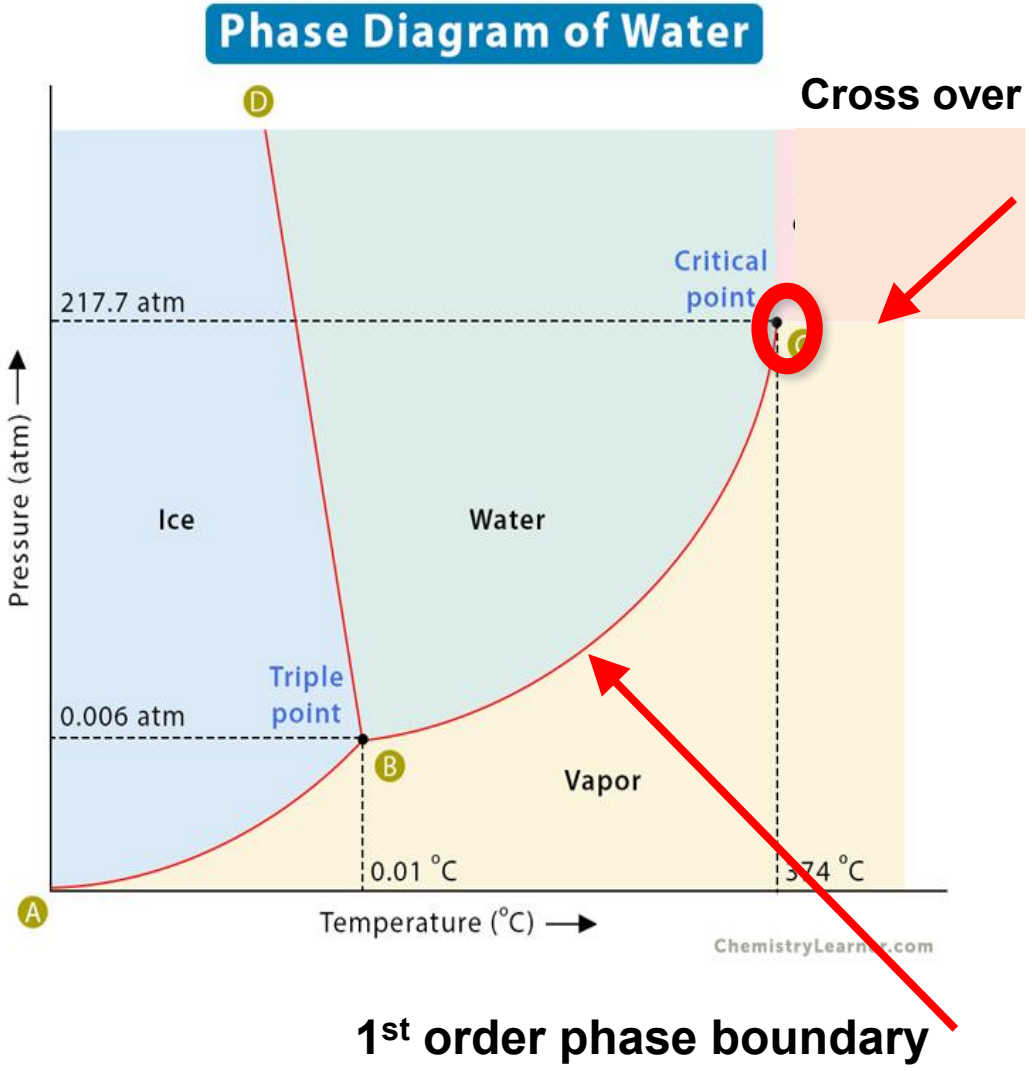
Overall good agreement between differential flow measurements

Relativistic Heavy-Ion Collisions and QCD Phase Diagram

Critical Temperature
$T_c \approx 156$ +/- 9 MeV

[PRD 90 094503 (2014)]

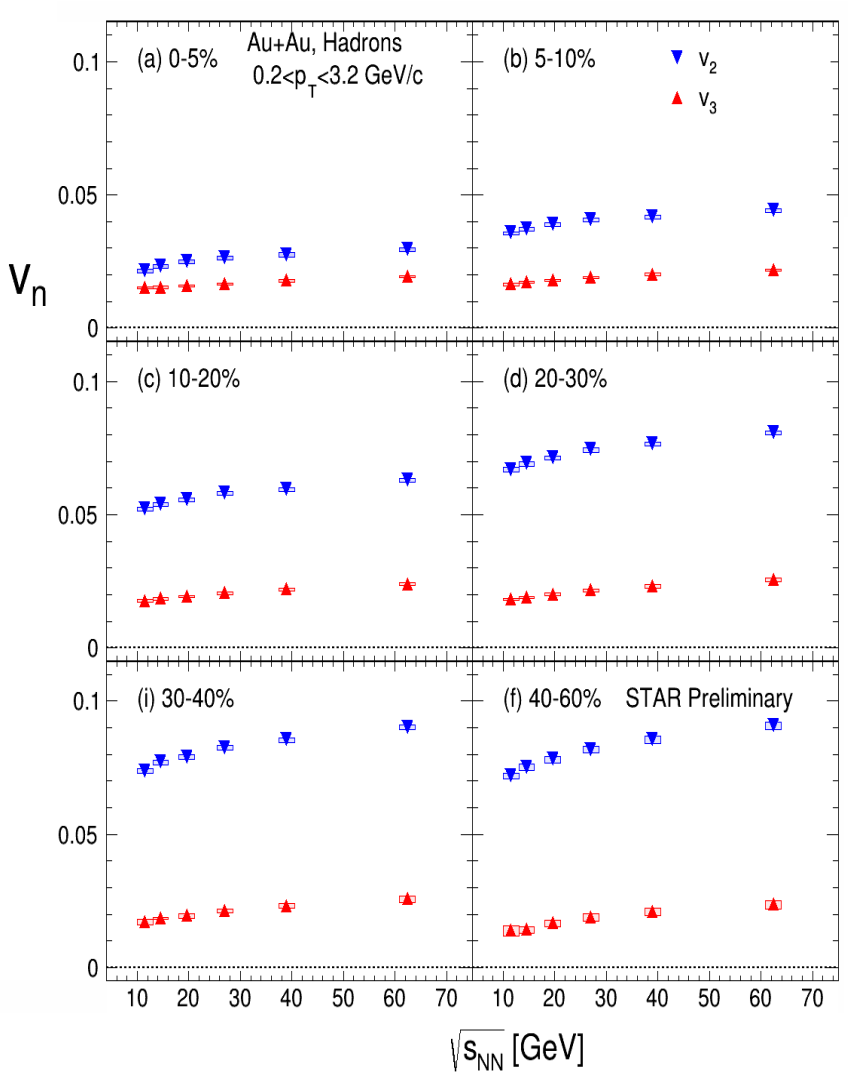


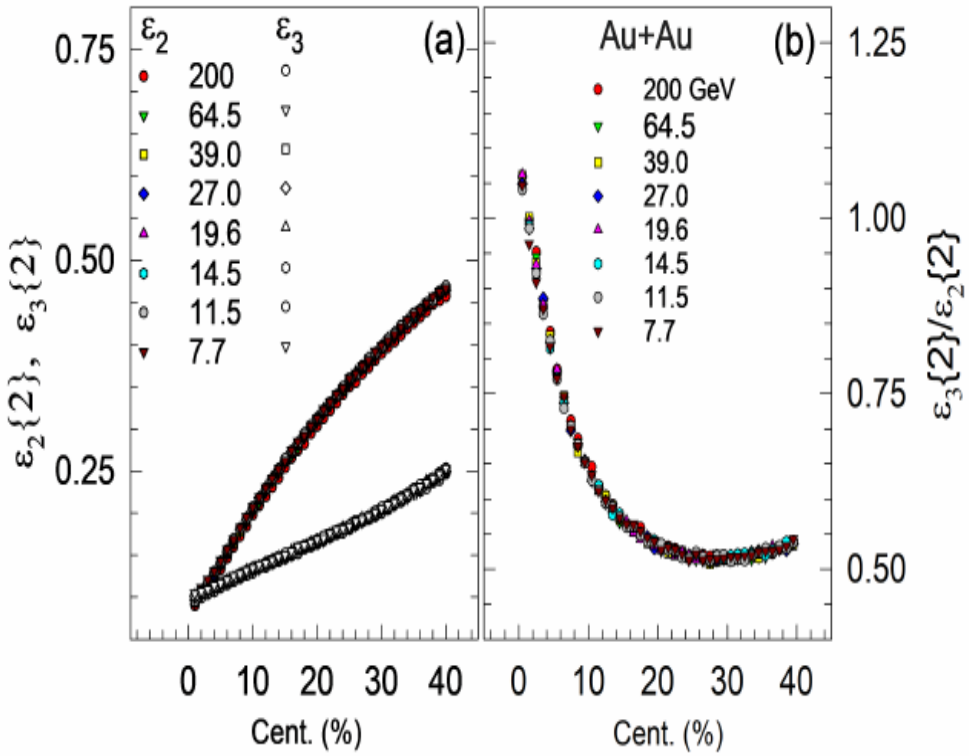


Smooth *transition from hadronic degrees of freedom to quark-gluon degrees of freedom at zero baryonic density*

Beam-energy dependence of v_2 and v_3

Petr Parfenov for STAR Collaboration,
J.Phys.Conf.Ser. 1690 (2020) 1, 012128

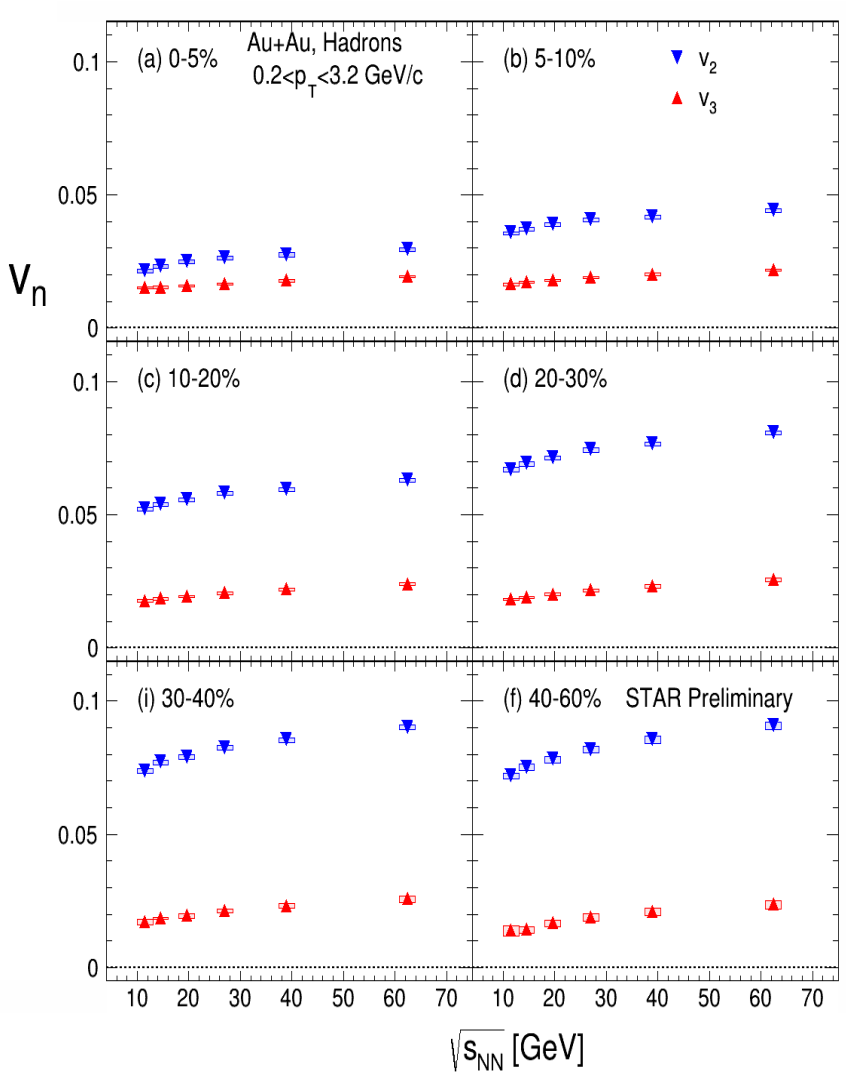


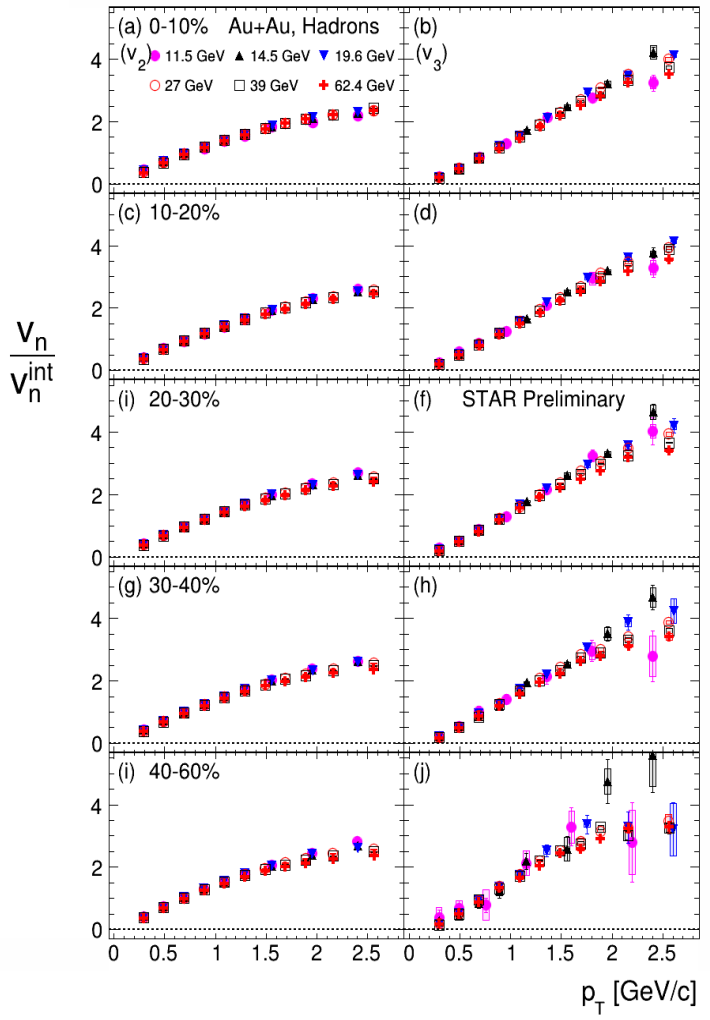


Integrated v_2 and v_3 decrease with decreasing collision energy

Beam-energy dependence of v_2 and v_3

J.Phys.Conf.Ser. 1690 (2020) 1, 012128

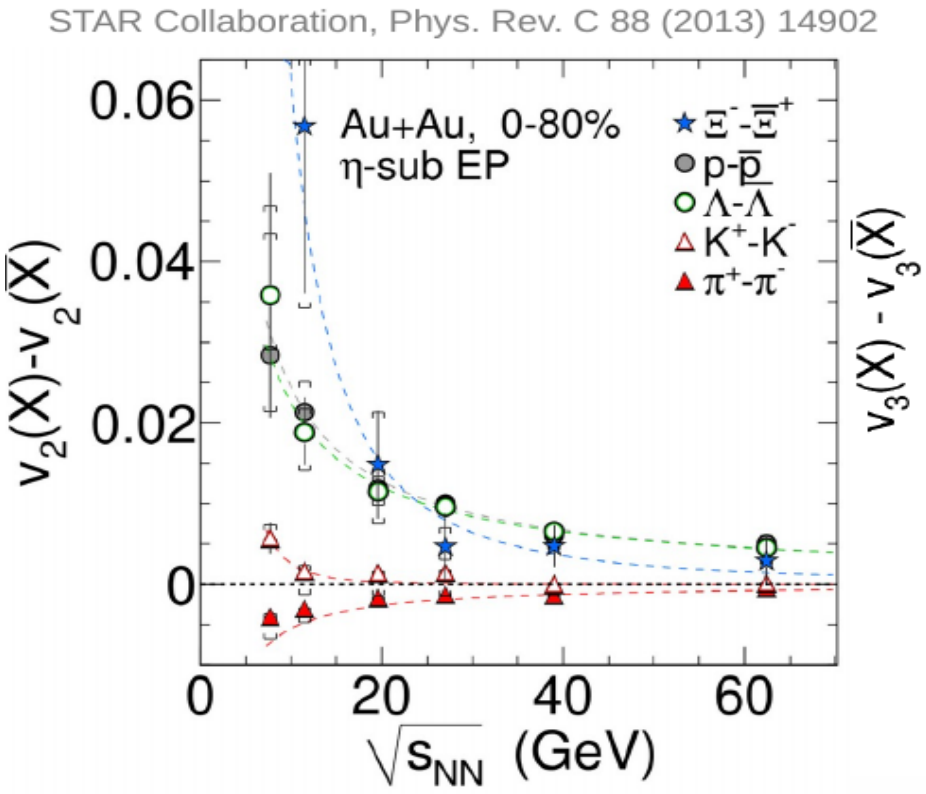




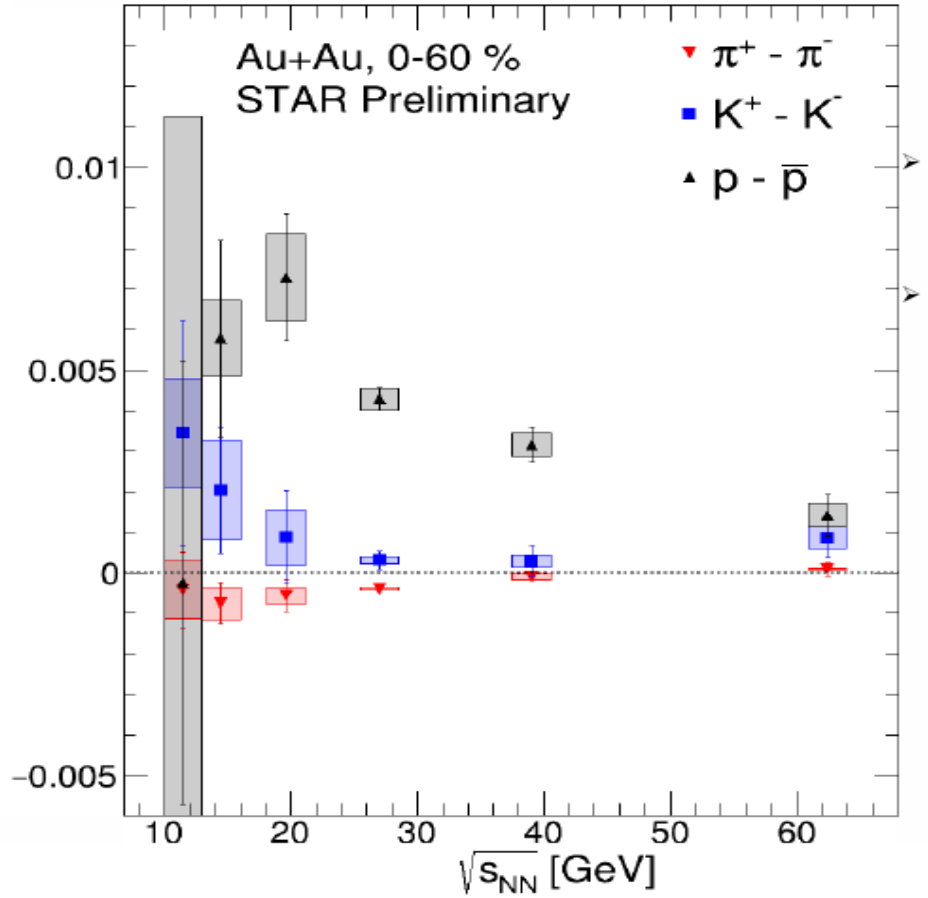
Integrated v_2 and v_3 decrease with decreasing collision energy

Similar shape of p_T dependence of normalized v_2 and v_3 for all centralities and collision energies

Anisotropic Flow of particles and antiparticles



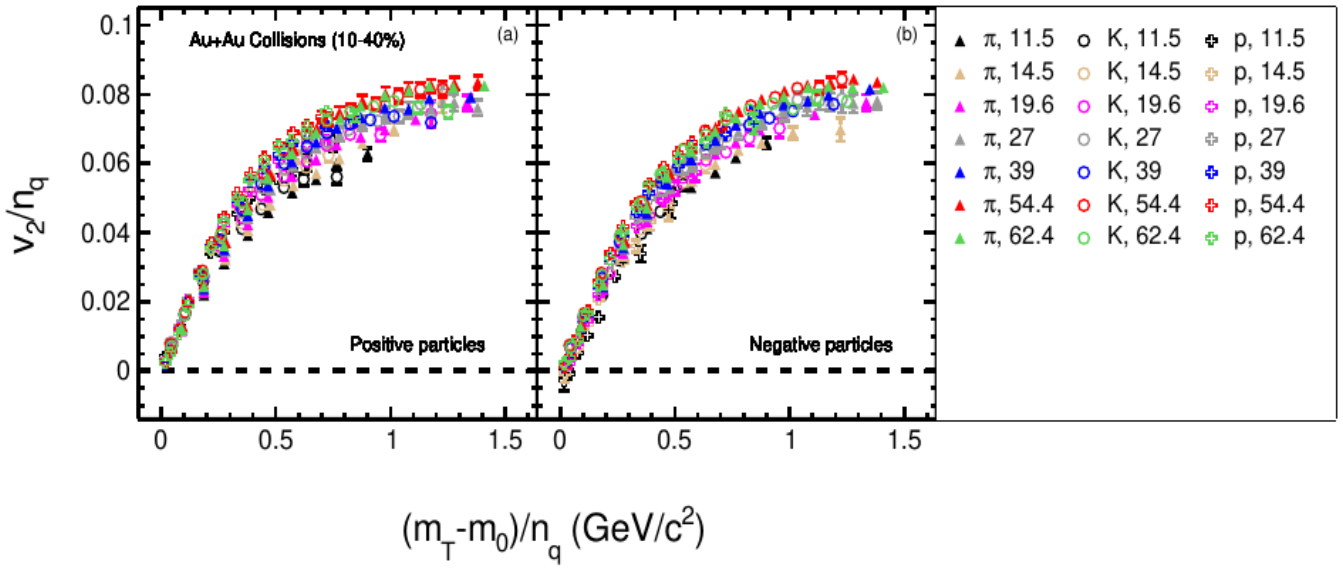
STAR Collaboration, Phys Rev C93, 14907 (2016)

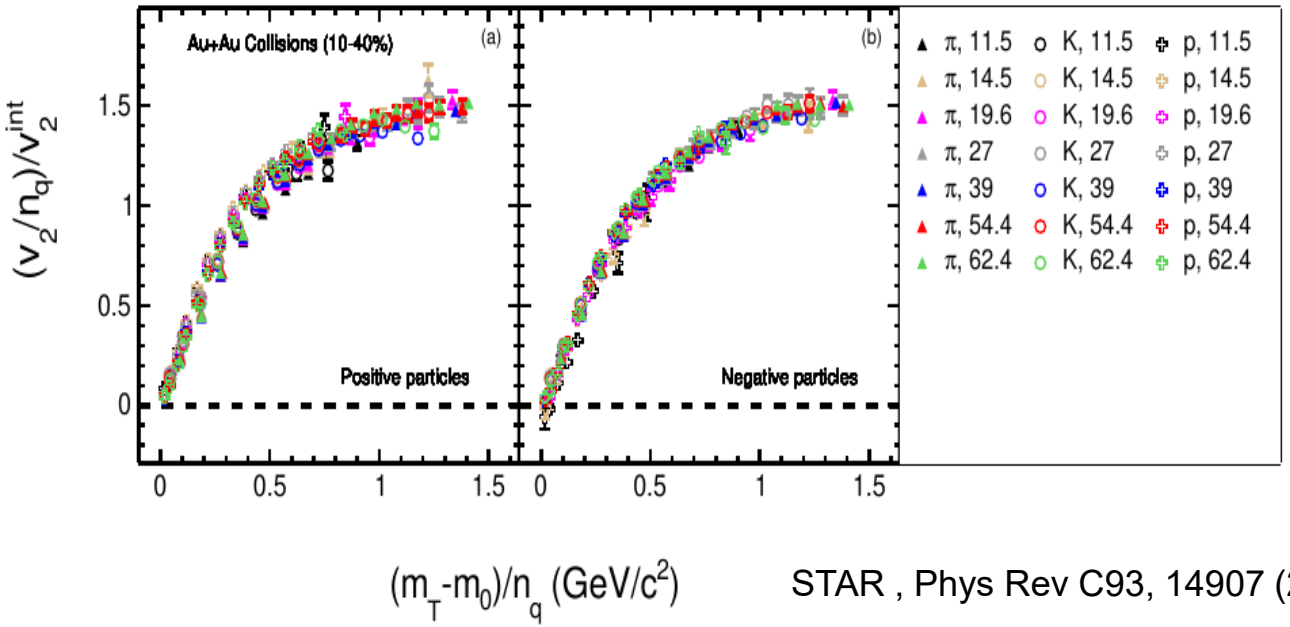


P. Parfenov *J.Phys.Conf.Ser.* 1690 (2020) 1, 012128

Energy-dependent difference in elliptic and riangular flow between particles and antiparticles. This difference is increasing with decreasing collision energy and is almost identical for all baryons. It is larger for baryons than mesons.

Elliptic flow from STAR BES program



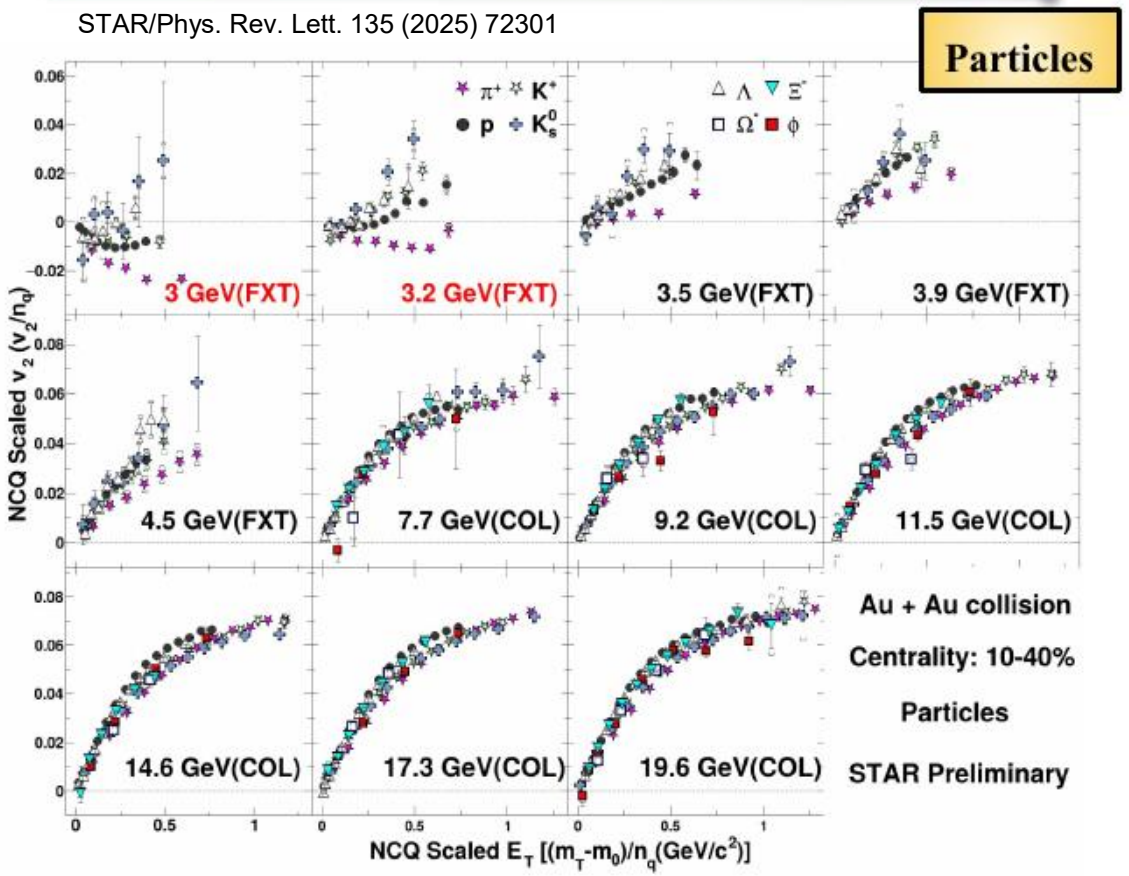


STAR , Phys Rev C93, 14907 (2016)

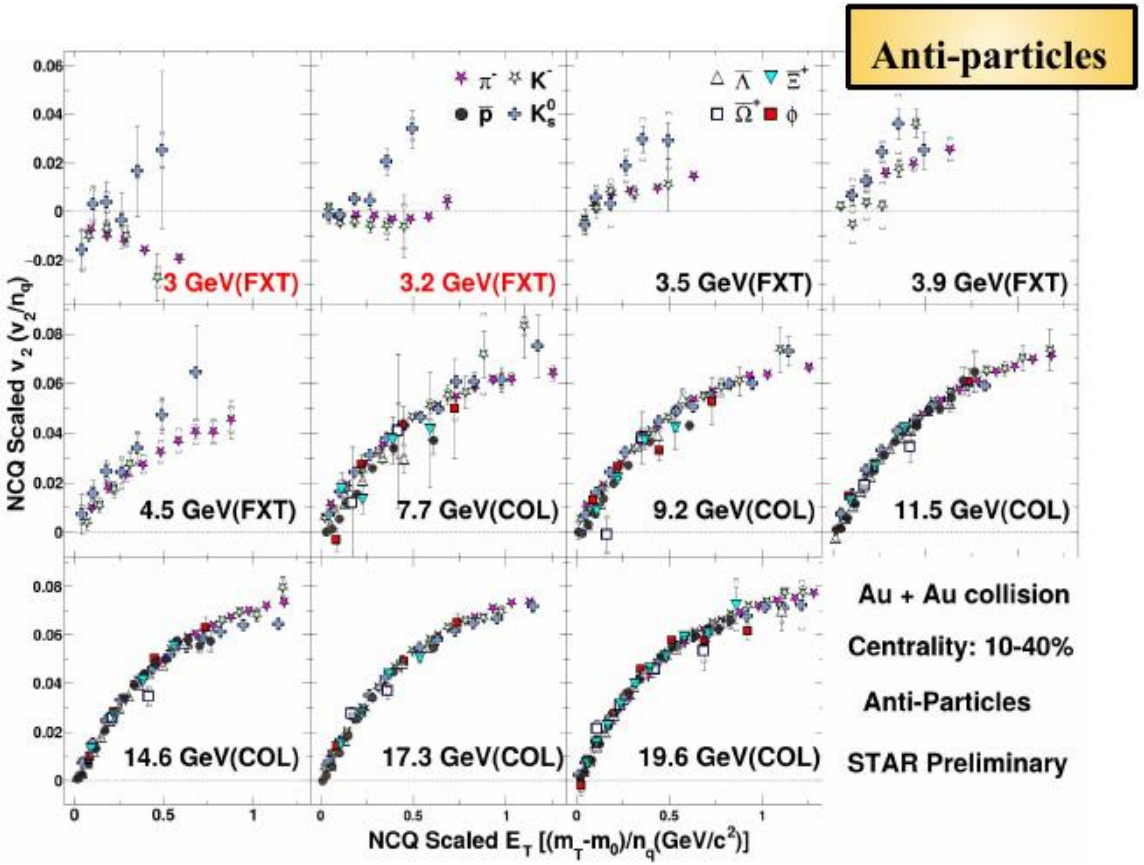
Observation of the Onset of Constituent Quark Number Scaling in Heavy-Ion Collisions at RHIC

NCQ scaled Elliptic flow

STAR/Phys. Rev. Lett. 135 (2025) 72301



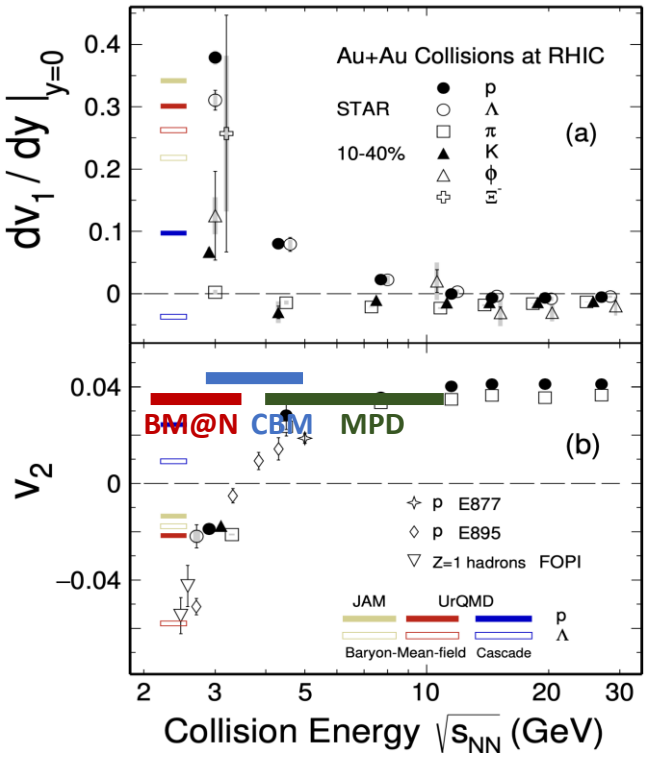
Is NCQ scaling the hallmark of the (s)QGP?
additive quark model ~ cross sections

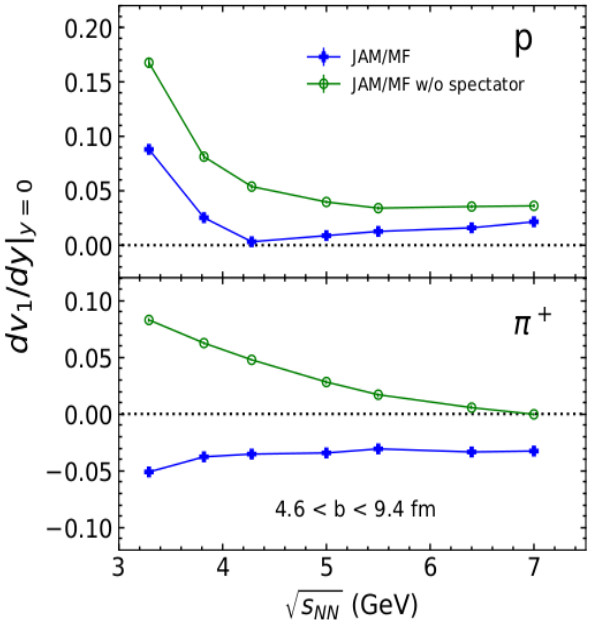


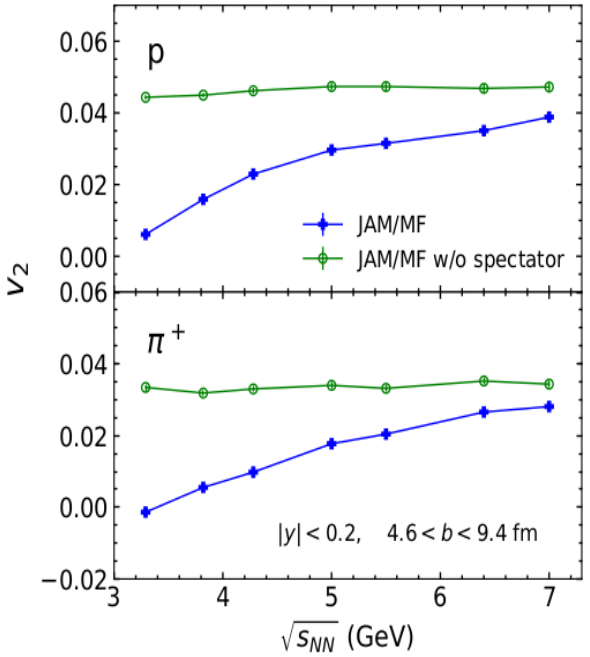
What is the cause of the failure of NCQ scaling below 7.7 GeV?

Anisotropic flow in heavy-ion collisions at high baryon density

M. Abdallah et al. STAR, Phys. Lett. B 827, 137003 (2022)







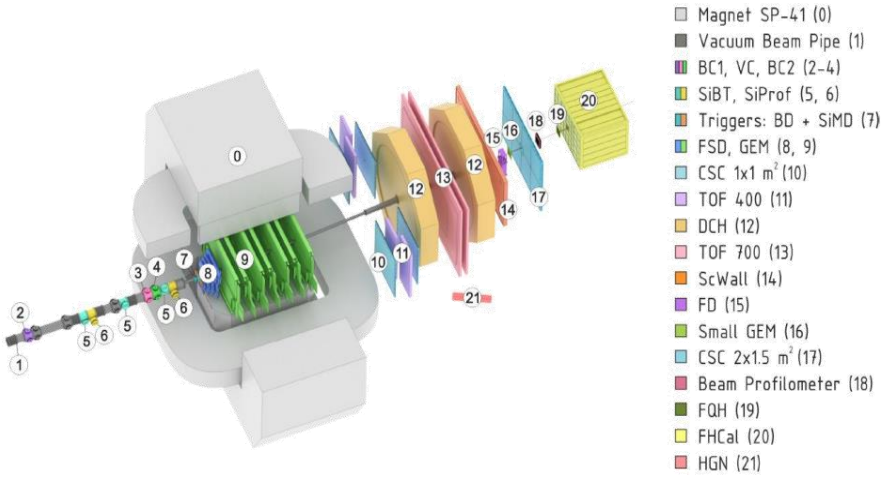
Phys. Rev. C 97, 064913 (2018)

Anisotropic flow at NICA energies is a delicate balance between:

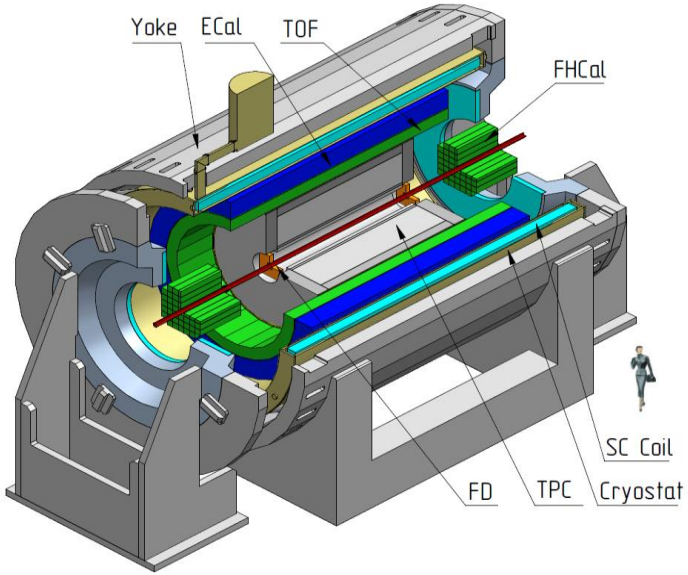
I. The ability of pressure developed early in the reaction zone ($t_{exp} = R/c_s, c_s = c\sqrt{dp/d\varepsilon}$)

II. The passage time for removal of the shadowing by spectators ($t_{pass} = 2R/\gamma_{CM}\beta_{CM}$)

Anisotropic Flow measurements at NICA (MPD + BM@N)



- Magnet SP-41 (0)
- Vacuum Beam Pipe (1)
- BC1, VC, BC2 (2-4)
- SiBT, SiProf (5, 6)
- Triggers: BD + SiMD (7)
- FSD, GEM (8, 9)
- CSC 1x1 m^2 (10)
- TOF 400 (11)
- DCH (12)
- TOF 700 (13)
- ScWall (14)
- FD (15)
- Small GEM (16)
- CSC 2x1.5 m^2 (17)
- Beam Profilometer (18)
- FQH (19)
- FHCal (20)
- HGN (21)

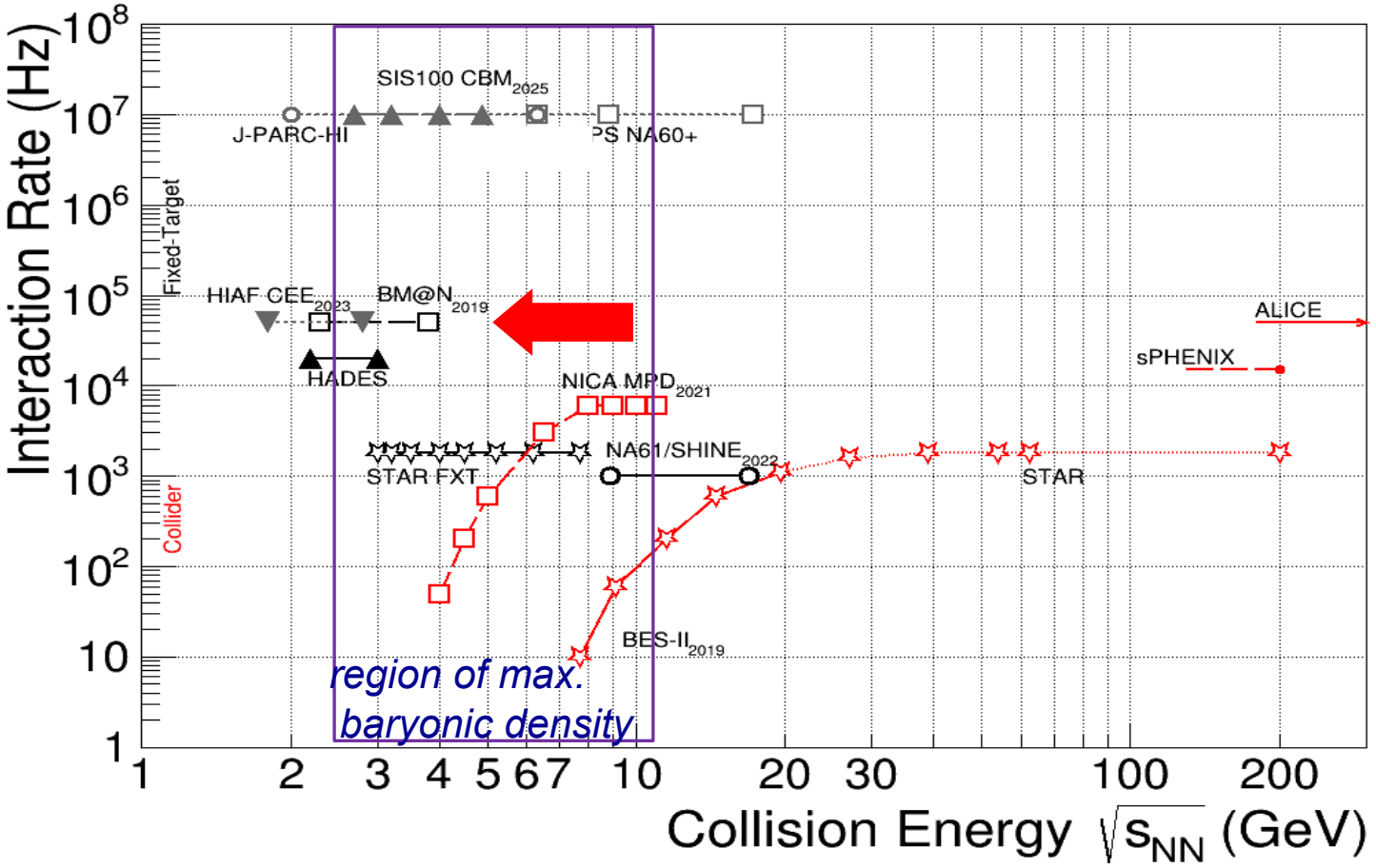




Selected publications: 2017-2025 (Anisotropic Flow measurements at NICA)

1) Flow performance in MPD at NICA, I. Svintsov, P. Parfenov, A. Taranenko, J Phys.Conf.Ser. 798 (2017) 1, 012067
2) Performance of the MPD experiment for the anisotropic flow measurements, P. Parfenov, A. Taranenko, KnE Energ.Phys. 3 (2018) 352-356
3) Performance studies of anisotropic flow with MPD at NICA, P. Parfenov, A. Taranenko, EPJ Web Conf. 204 (2019) 07010
4) Methods for anisotropic flow measurements with the MPD Experiment at NICA, D. Idrisov, P.Parfenov, A. Taranenko, J. Phys. Conf. Ser. 1690 (2020) 1, 012129
5) Status of the mega-science project NICA, A. Taranenko, J. Phys. Conf. Ser. 1685 (2020) 1, 012021
6) Anisotropic Flow Measurements at NICA Energies, A. Taranenko et al., Phys. Part. Nucl. 51 (2020) 3, 309-313
7) Anisotropic Flow Measurements with Multi-Purpose Detector at NICA, A. Taranenko et. al. Acta Phys. Polon. Supp. 14 (2021) 3, 515-518
8) Evolution of elliptic flow of produced particles from Au+Au collisions at 4.5−200 Gev in a hybrid model, A. Demanov, P Parfenov, A. Taranenko, AIP Conf.Proc. 2377 (2021) 1, 030003
9) Performance for Directed Flow Measurements of the MPD Experiment at NICA, P. Parfenov et al. Phys.Part.Nucl. 52 (2021) 4, 618-623
10) Methods for Elliptic Flow Measurements with the MPD Experiment at NICA, D. Idrisov, P. Parfenov, A Taranenko, Phys.Part.Nucl. 52 (2021) 4, 637-643
11) Relating Charged Particle Multiplicity to Impact Parameter in Heavy-Ion Collisions at NICA Energies, P. Parfenov, A. Taranenko, Particles 4 (2021) 2, 275-287
12) Anisotropic Flow Measurements of Identified Hadrons with MPD Detector at NICA, Petr Parfenov et al , Particles 4 (2021) 2, 146-158
13) Status and initial physics performance studies of the MPD experiment at NICA , V. Abgaryan, A. Taranenko et al. (MPD) Eur.Phys.J.A 58 (2022) 7, 140
10) Model study of the energy dependence of the correlation between anisotropic flow and the mean transverse momentum in Au+Au collisions, N. Magdy, P. Parfenov, A. Taranenko, R. Lacey, Phys. Rev. C 105 (2022) 4, 044901
11) Elliptic Flow and Its Fluctuations from Transport Models for Au+Au Collisions at 7.7 and 11.5 GeV, V. Ba Luong, P. Parfenov, A. Taranenko, Particles 6 (2022) 1, 17
12) Model Study of the Energy Dependence of Anisotropic Flow in Heavy-Ion Collisions at 2–4.5 GeV, P. Parfenov, Particles 5 (2022) 4, 561-579
13) Scaling Properties of Anisotropic Flow at Nuclotron-NICA Energies, P. Parfenov, A. Taranenko, Phys. Atom. Nucl. 86 (2023) 6, 1493
14) Toward the System Size Dependence of Anisotropic Flow in Heavy-Ion Collisions at 2–5 GeV, M. Mamaev, A. Taranenko Particles 6 (2023) 2, 622-637
15) Centrality Selection Effect on Elliptic Flow Measurements in Relativistic Heavy-Ion Collisions at NICA Energies, D. Idrisov, P. Parfenov, A. Taranenko, Particles 6 (2023) 2, 497-514
16) Flow Measurements of Identified Hadrons with Fixed-Target Mode of MPD at NICA, P. Parfenov, M. Mamaev, A. Taranenko, Phys. Part. Nucl. 55 (2024) 4, 853
17) Elliptic Flow Fluctuations at NICA Energy Range, A. Demanov, P. Parfenov, A. Taranenko, Phys.Part.Nucl. 55 (2024) 4, 1124-1128
18) MPD physics performance studies in Bi+Bi collisions at 9.2 GeV, Rev.Mex.Fis. 71 (2025) 4, 041201, R. Abdulin, A. Taranenko et al. (MPD Collaboration)

Relativistic Heavy Ion Collision Experiments



MPD, BM@N competitors:

Present:

RHIC/STAR (USA) 3-200 GeV
NA61/SHINE (CERN): 5.1-17.3 GeV
SIS18/HADES (Germany) 2.4-2.55 GeV

Future:

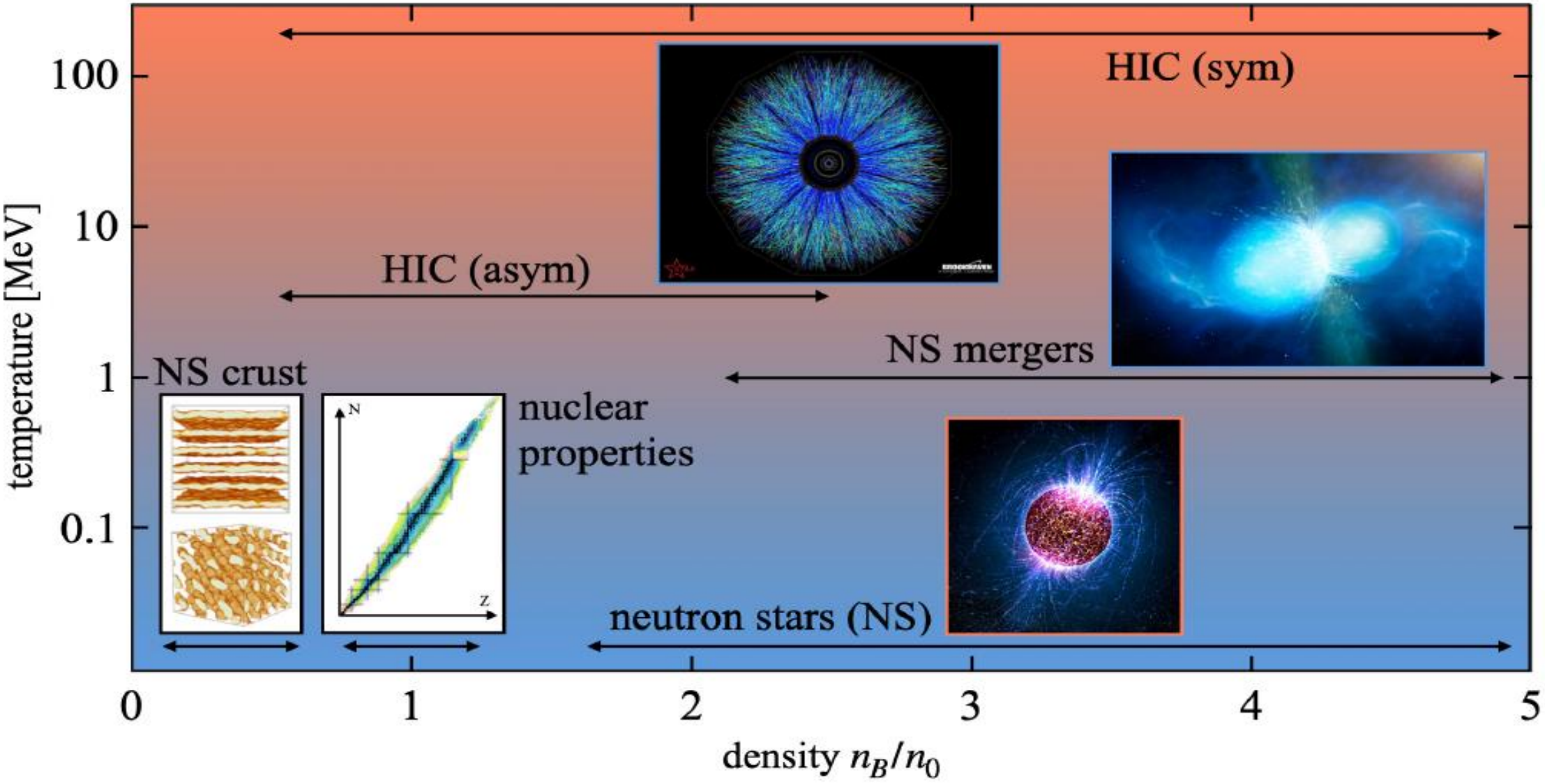
HIAF/CEE (China) 2.1-4.5 GeV (2026-?)
FAIR/CBM (Germany) 2.4-4.9 GeV (2029-?)
JPARC-HI (Japan) 2-5 GeV (2030-?)
NA60+(CERN) 6.1-16.4 GeV (2029-?)

Method	μ_c (MeV)	T_c (MeV)
Holography + Bayesian	560 - 625	101 - 108
FRG/DSE	495 - 654	108 - 119
Lee-Yang edge singularities	500 - 600	100 - 105
Lattice QCD	$\mu_c/T_c > 3$	F. Karsch et al.
Summary	**495 - 654**	**100 - 119**

$(\mu_c, T_c) = (495 - 654, 100 - 119)$ MeV ➡ $3.5 < \sqrt{s_{NN}} < 4.9$ GeV

BM@N and MPD are both in the collision energy range of the predicted CEP location.

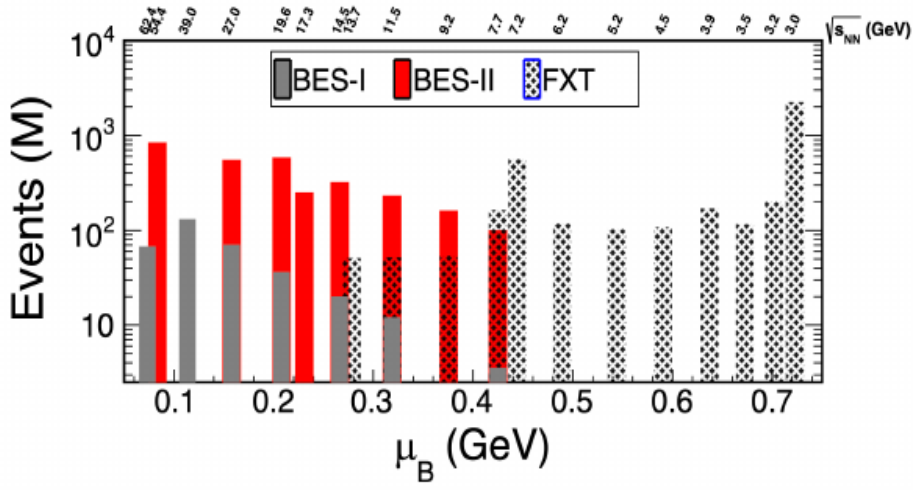
Dense Nuclear Matter



Relativistic heavy-ion collisions provide a unique and controlled experimental way to study the properties of nuclear matter at high baryon density.

Beam Energy Scan programs

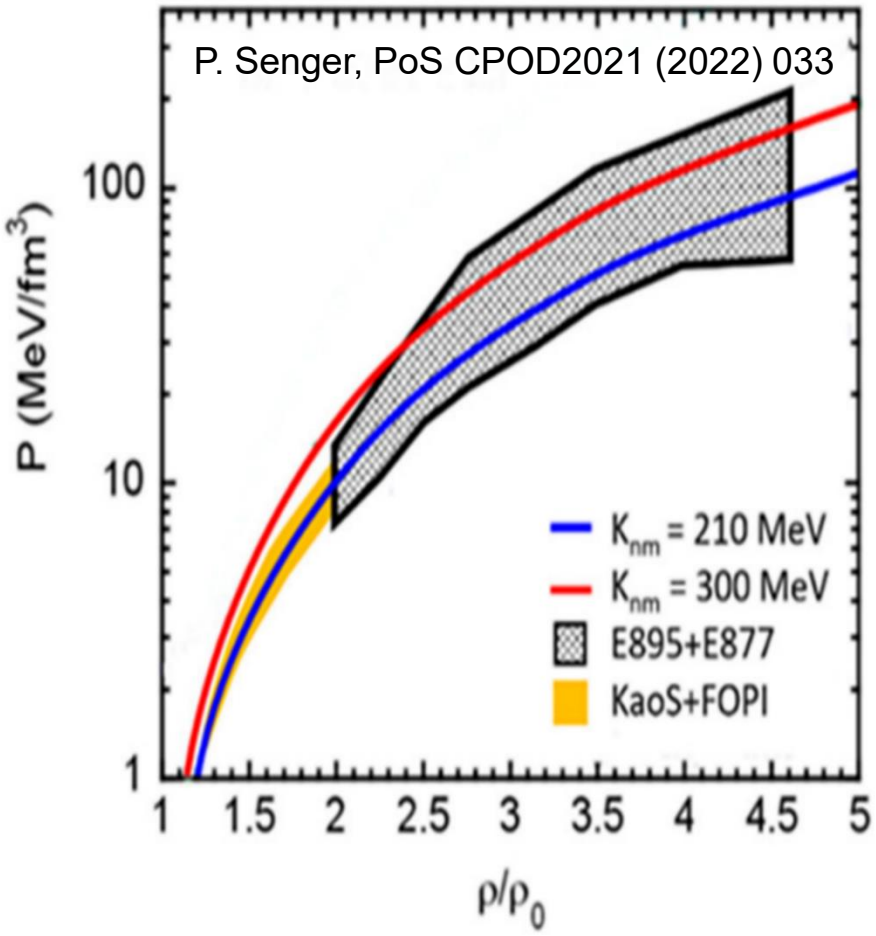
STAR at RHIC: $3 < \sqrt{s_{NN}} < 200$ GeV ($750 < \mu_B < 25$ MeV)

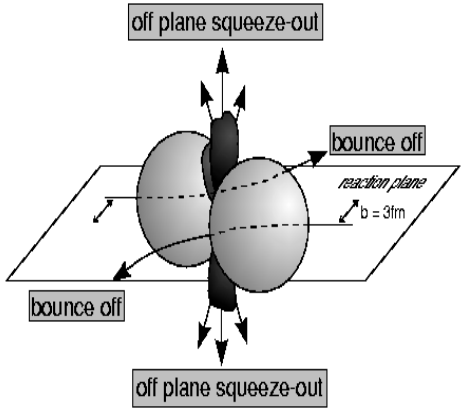


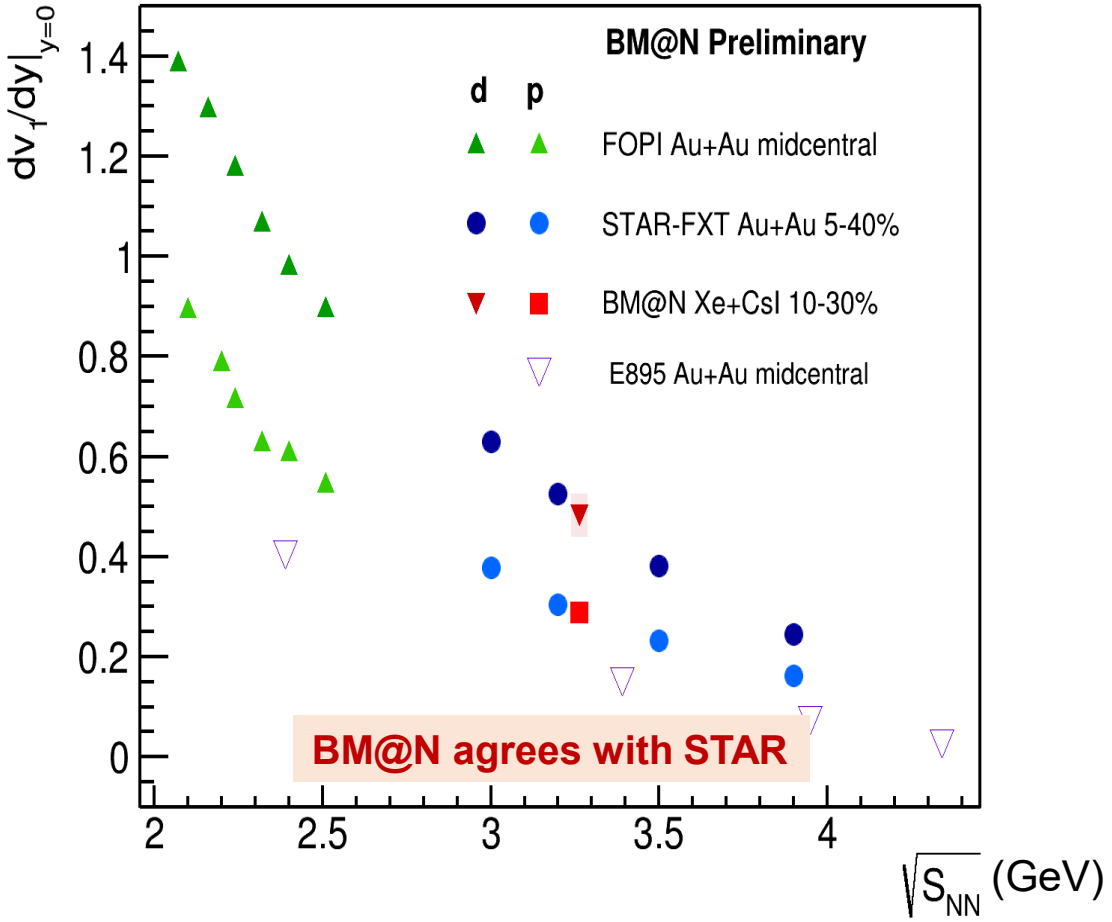
Au+Au Collisions at RHIC

Collider Runs						Fixed-Target Runs					
	$\sqrt{s_{NN}}$ (GeV)	#Events	μ_B	y_{beam}	run		$\sqrt{s_{NN}}$ (GeV)	#Events	μ_B	y_{beam}	run
1	200	380 M	25 MeV	5.3	Run-10, 19	1	13.7 (100)	50 M	280 MeV	-2.69	Run-21
2	62.4	46 M	75 MeV		Run-10	2	11.5 (70)	50 M	320 MeV	-2.51	Run-21
3	54.4	1200 M	85 MeV		Run-17	3	9.2 (44.5)	50 M	370 MeV	-2.28	Run-21
4	39	86 M	112 MeV		Run-10	4	7.7 (31.2)	260 M	420 MeV	-2.1	Run-18, 19, 20
5	27	585 M	156 MeV	3.36	Run-11, 18	5	7.2 (26.5)	470 M	440 MeV	-2.02	Run-18, 20
6	19.6	595 M	206 MeV	3.1	Run-11, 19	6	6.2 (19.5)	120 M	490 MeV	1.87	Run-20
7	17.3	256 M	230 MeV		Run-21	7	5.2 (13.5)	100 M	540 MeV	-1.68	Run-20
8	14.6	340 M	262 MeV		Run-14, 19	8	4.5 (9.8)	110 M	590 MeV	-1.52	Run-20
9	11.5	157 M	316 MeV		Run-10, 20	9	3.9 (7.3)	120 M	633 MeV	-1.37	Run-20
10	9.2	160 M	372 MeV		Run-10, 20	10	3.5 (5.75)	120 M	670 MeV	-1.2	Run-20
11	7.7	104 M	420 MeV		Run-21	11	3.2 (4.59)	200 M	699 MeV	-1.13	Run-19
						12	3.0 (3.85)	2000 M	750 MeV	-1.05	Run-18, 21

Directed flow of protons and EOS of symmetric matter





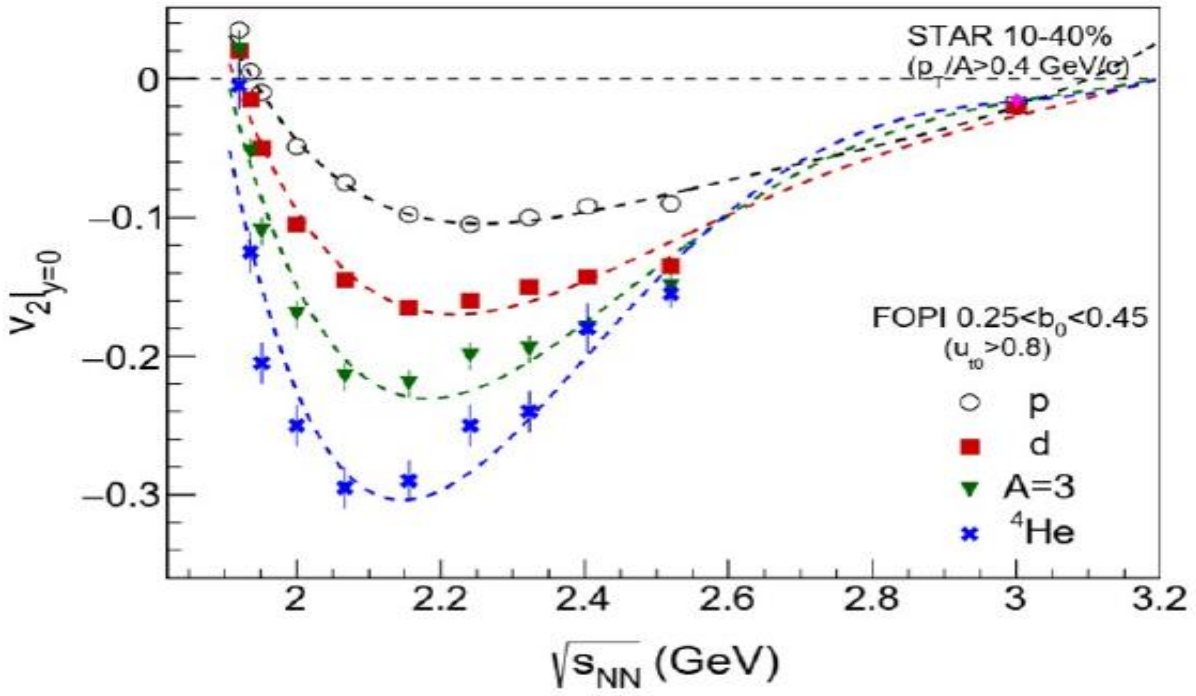


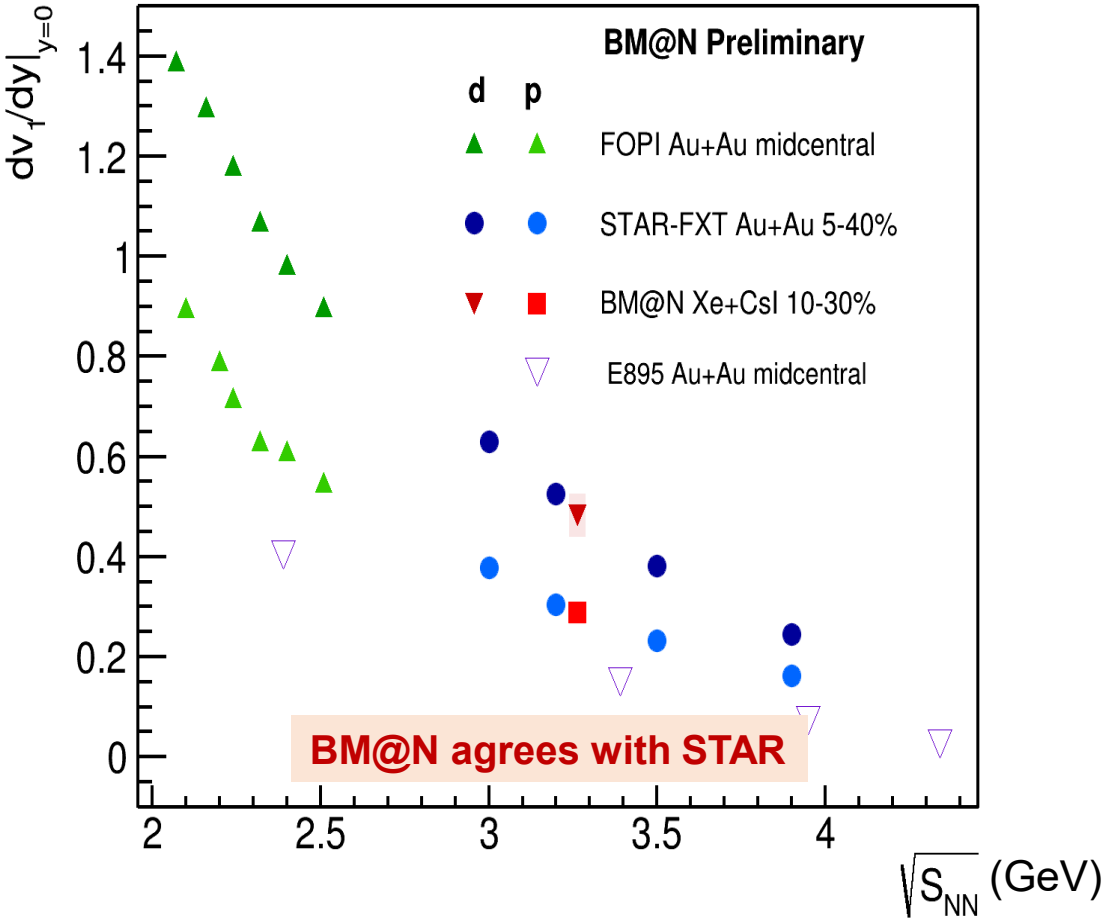
Nuclear incompressibility from collective proton flow

P. Danielewicz, R. Lacey, W.G. Lynch, Science 298 (2002) 1592

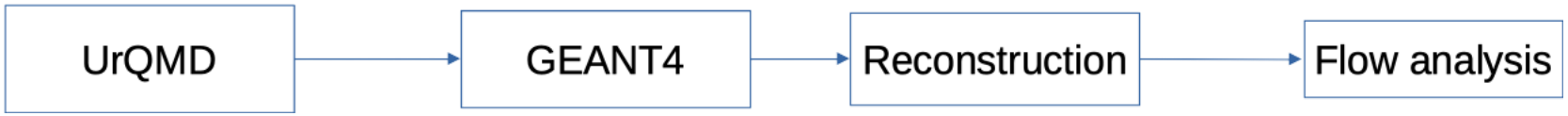
Both STAR and BM@N results for directed flow prefer stiff EOS

Directed and elliptic flow and EOS of symmetric matter

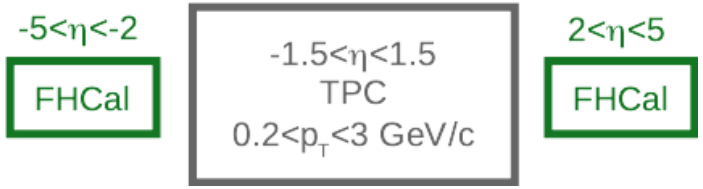


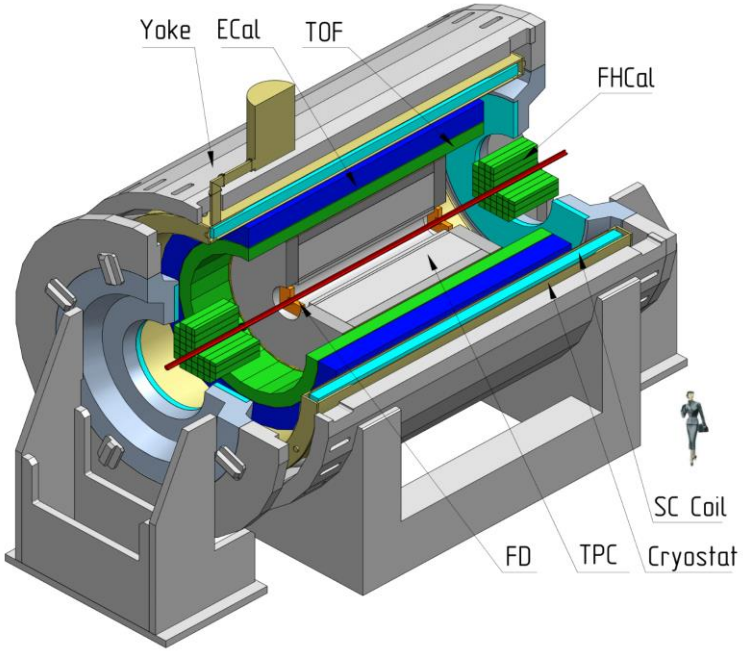


MPD Experiment at NICA



- Bi+Bi: 50M at $\sqrt{s_{NN}}$ = 9.2 GeV (prod. 25)
- Centrality determination: Bayesian inversion method and MC-Glauber
- Event plane determination: TPC, FHCal
- Track selection:
  - Primary tracks
  - $N_{TPC\ hits} \geq 16$
  - $0.2 < p_T < 3.0$ GeV/c
  - $|\eta| < 1.5$
  - PID – ToF + dE/dx

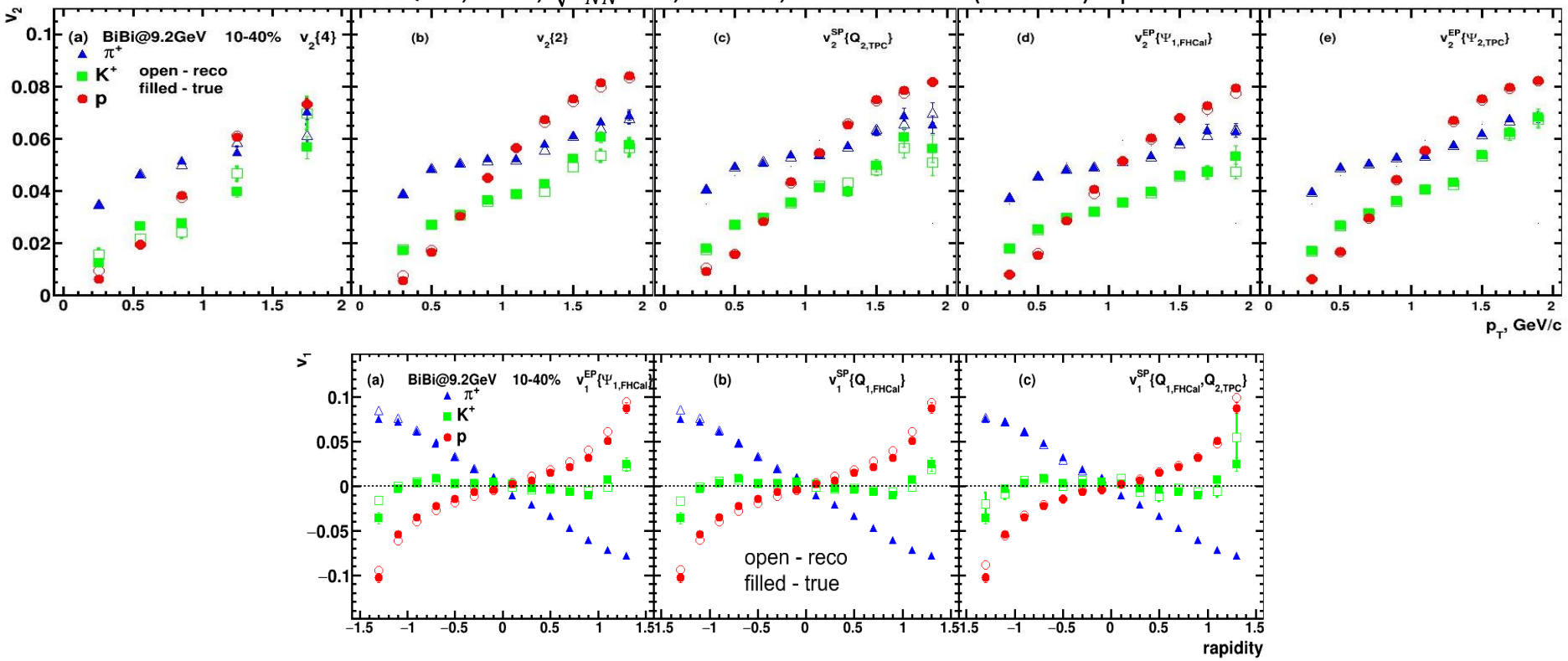




Multi-Purpose Detector (MPD) Stage 1

Performance of $v_{1,2}$ of identified hadrons in MPD

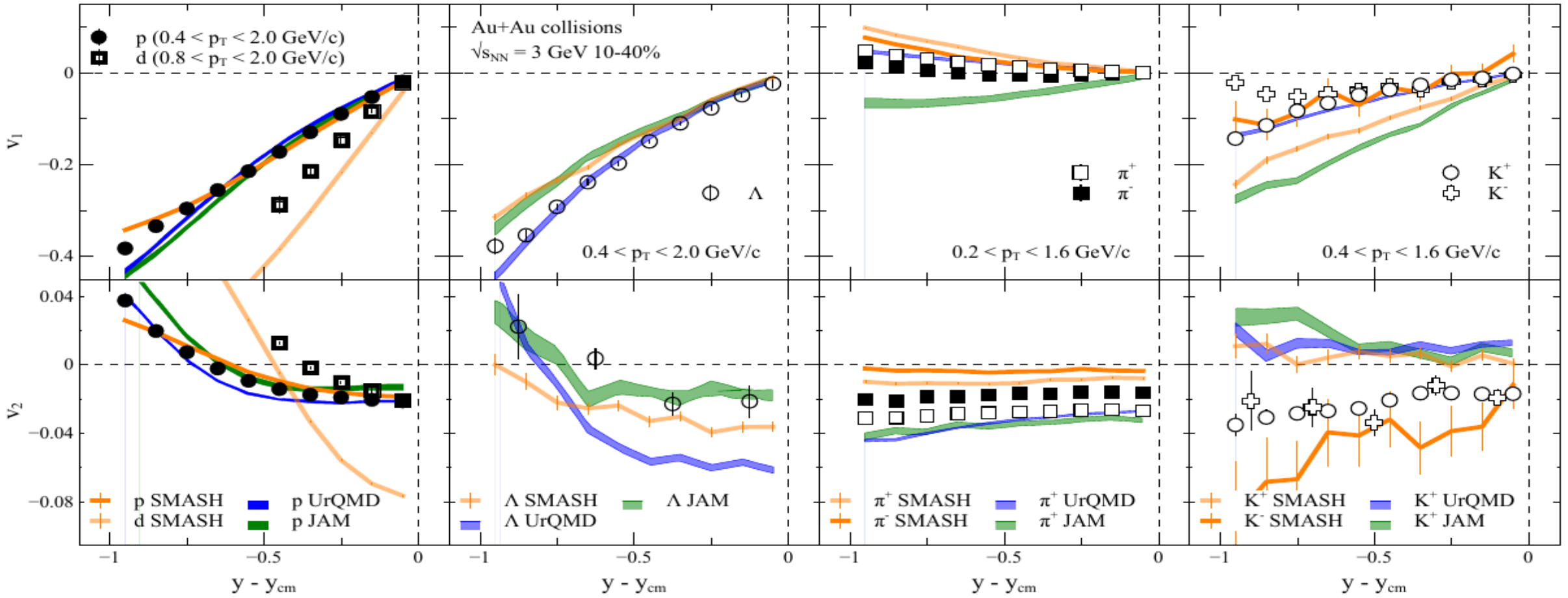
UrQMD, Bi+Bi, $\sqrt{s_{NN}}$=9.2, 10-40%, reconstructed (GEANT4) – production 25



Reconstructed and generated $v_{1,2}$ of identified hadrons have a good agreement for all methods

Describing proton flow is not enough

Prog.Part.Nucl.Phys. 134 (2024) 104080



Strange baryons are not well described
— the results may depend on:
• nucleon-hyperon and hyperon-hyperon interactions
• in-medium modifications of interactions

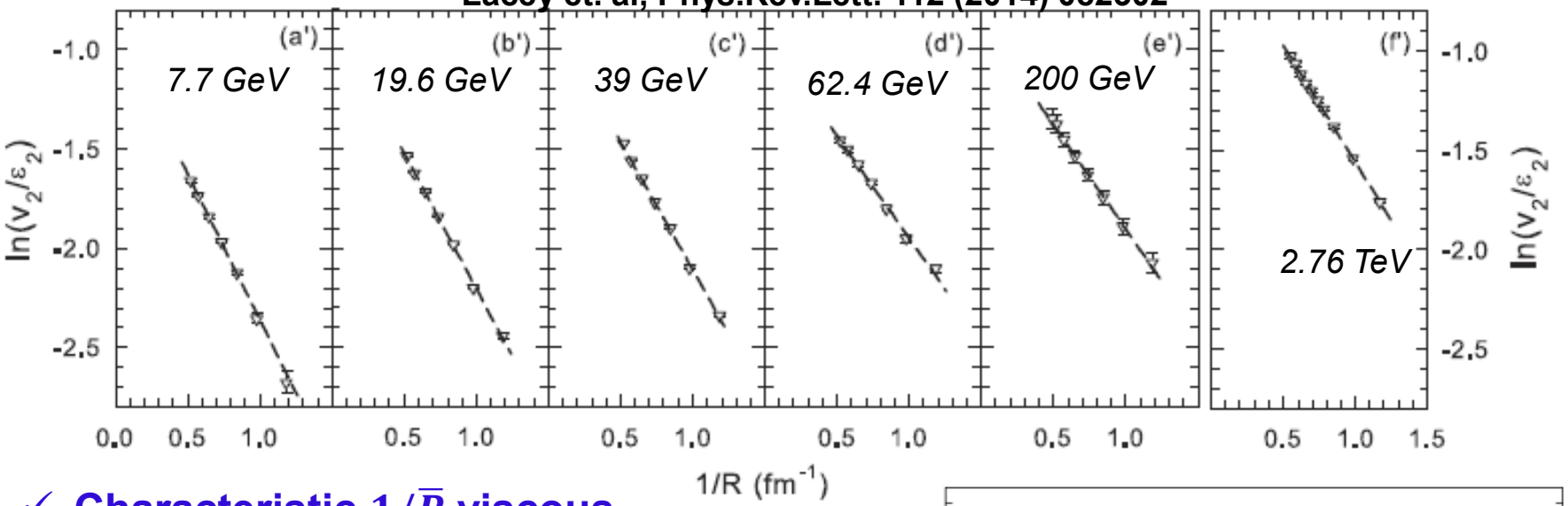
Pions and kaons NOT described!
Not very surprising: UrQMD, JAM, and SMASH don't have mean-fields for mesons

Scaling properties of flow

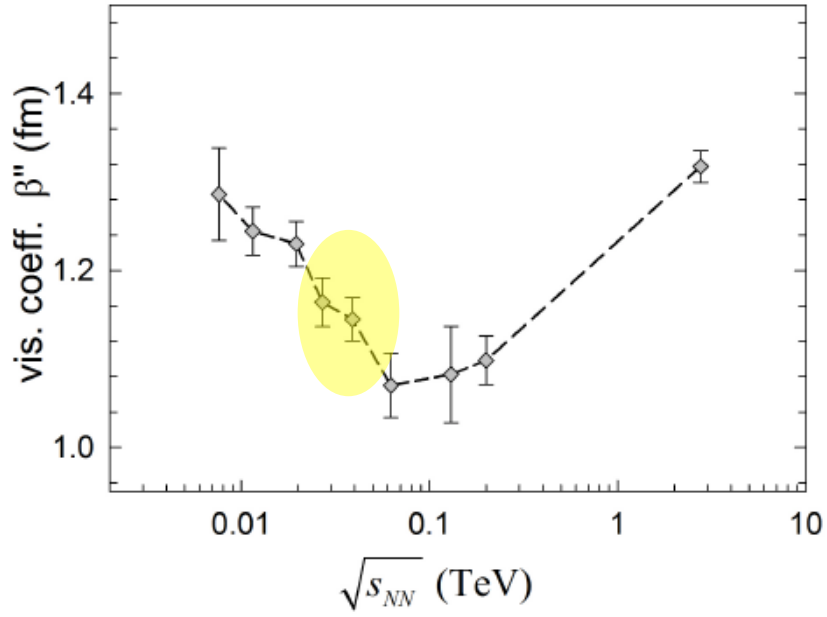
$$\ln\left(\frac{v_n}{\varepsilon_n}\right) \propto \frac{-\beta''}{\bar{R}}$$

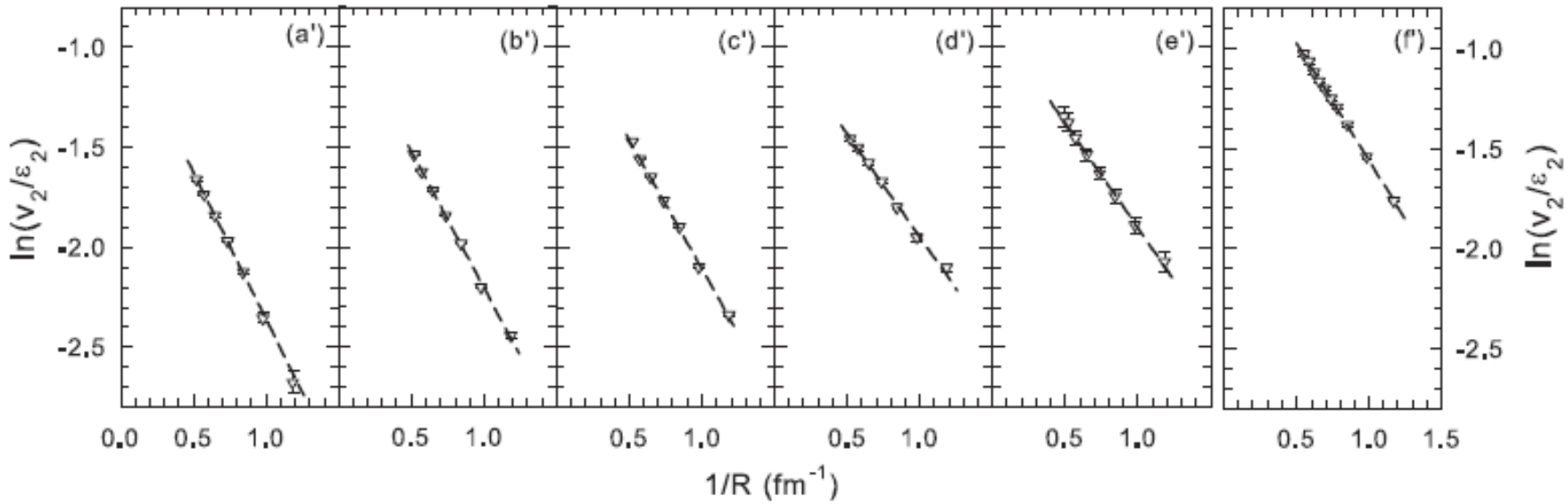
Acoustic Scaling – $\frac{1}{\bar{R}}$ Scaling for the Beam Energy Scan

Lacey et. al, Phys.Rev.Lett. 112 (2014) 082302



- ✓ **Characteristic $1/\bar{R}$ viscous damping validated across beam energies**
- ✓ **Experimental indications for *η/s variation in the* (T, μ_B)-plane**
- ✓ **CEP?**

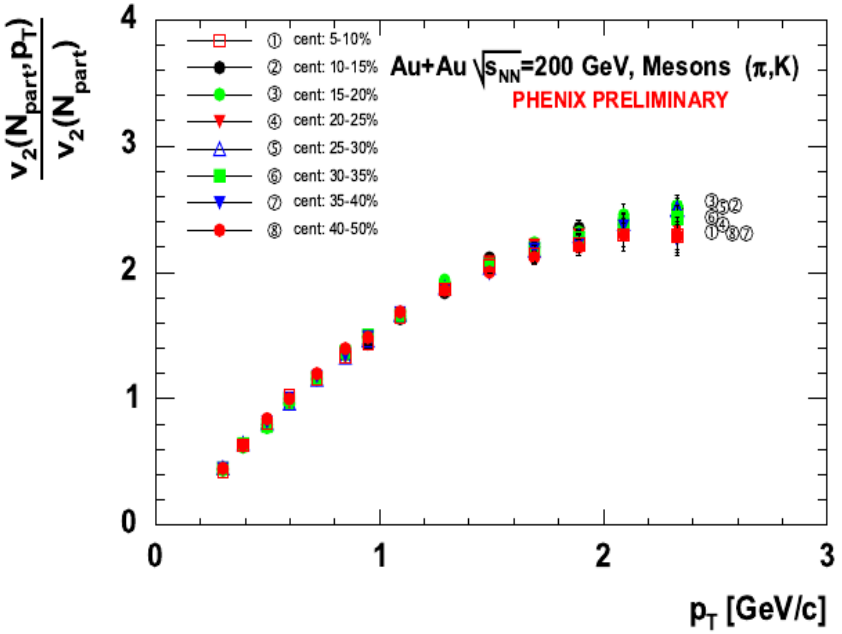



(a')
(b')
(c')
(d')
(e')
(f')
ln(v2/ε2)
-1.0
-1.5
-2.0
-2.5
0.0
0.5
1.0
1.5
1/R (fm-1)

Scaling properties of azimuthal anisotropy of mesons and baryons at RHIC,

A. Taranenko, Acta Phys. Hung. A 25 (2006) 371-379

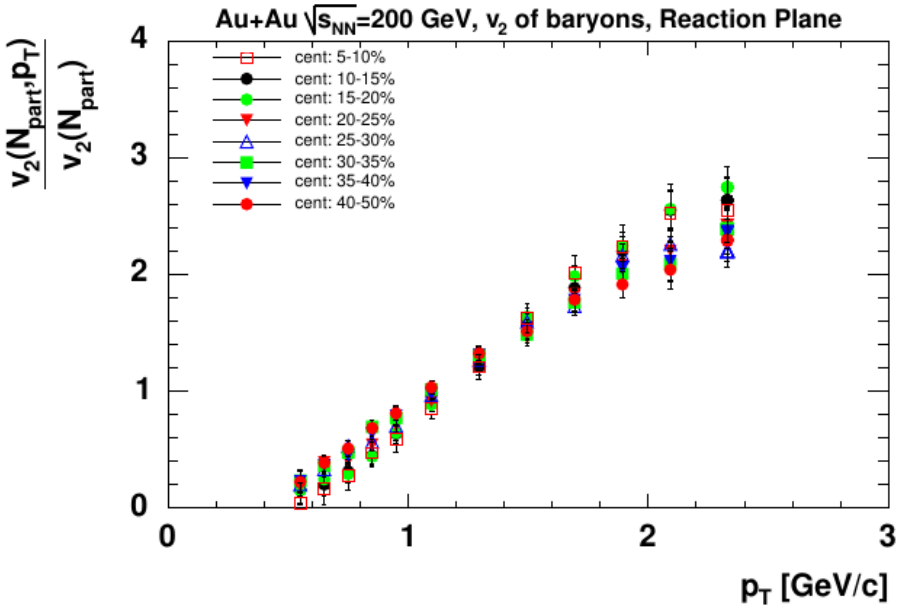
21st Winter Workshop on Nuclear dynamics, 2005, Breckenridge, USA

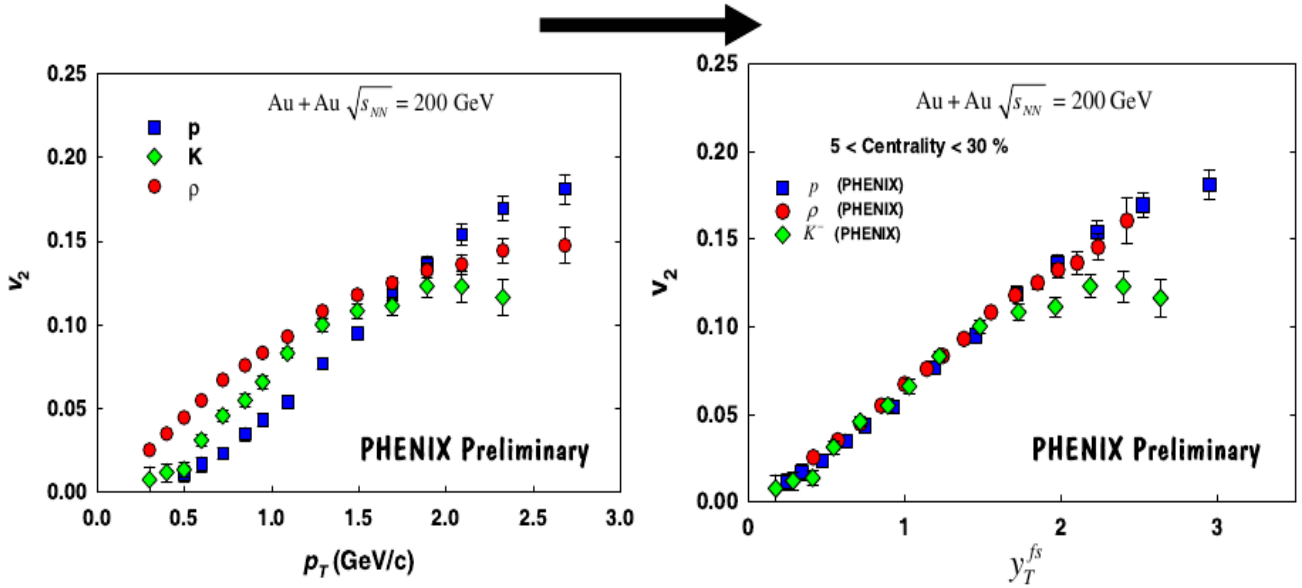


flavor scaling via substitution of the transverse rapidity [21], $y_T = \sinh^{-1}(p_T/m)$ in Eq. (2) to give

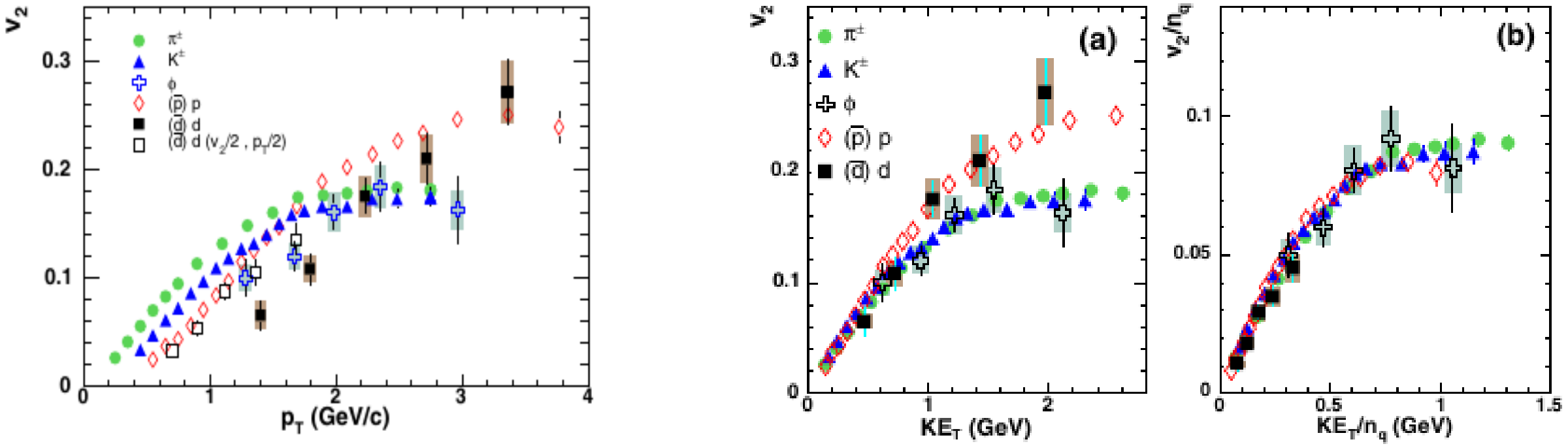
$$v_2 = k_1 y_T^2 \frac{m}{T_0}\left(1 + \frac{k_2}{k_1}\frac{T_0}{m} + \frac{k_3}{k_1}\frac{T_0^2}{m}\ldots\right), \qquad (5)$$

where, $k_1, k_2, k_3, \ldots$ are largely governed by the expansion rate. Close inspection of the leading term in Eq. 5 indicates that v_2 for different particle species should scale with $y_T^{\rm fs} = k_m \cdot y_T^2 m$. Here k_m is a mass dependent factor which is $\simeq$1 for relatively heavy particles. It is straightforward to show that hydrodynamics also predicts that





Elliptic Flow for ϕ Mesons and (Anti)deuterons in Au + Au Collisions at $\sqrt{s_{NN}} = 200$ GeV



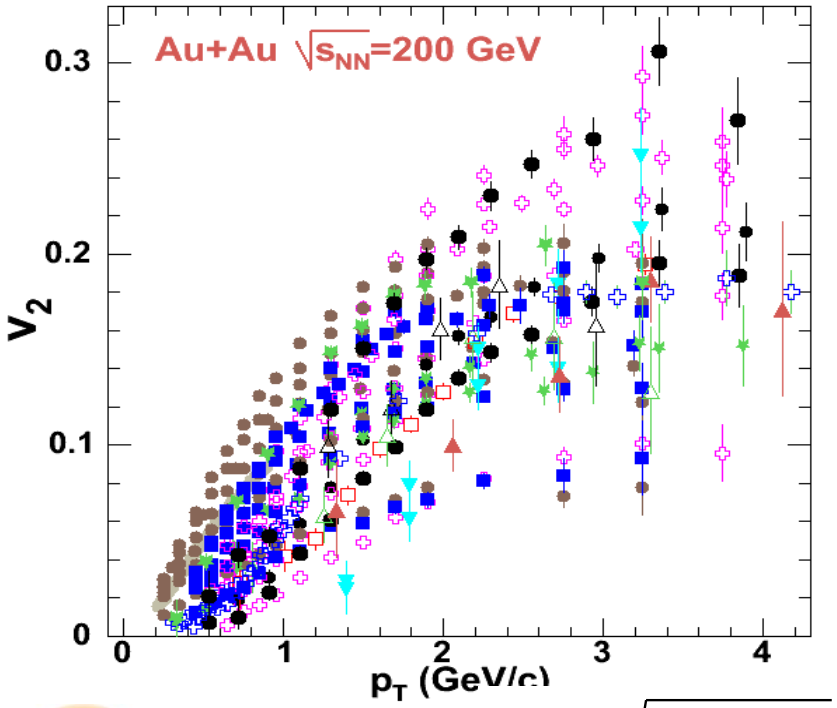
Gordon Research Conference 2006 (New London, USA, 2006 r.)

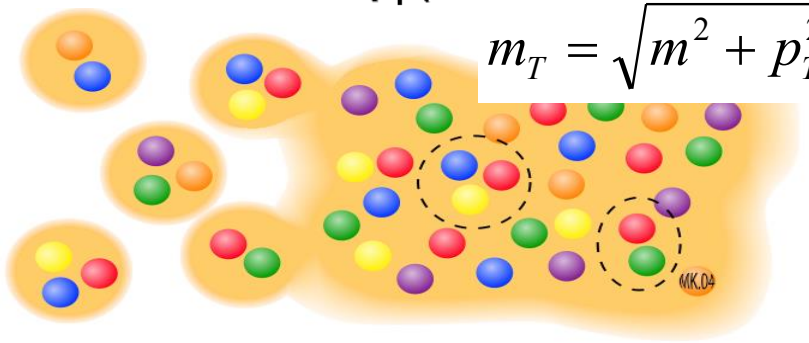
Quark Matter 2006 (Shanghai, China, 2006 r.),

What do elliptic flow measurements tell us about the matter created in the little bang at RHIC?, R.A. Lacey, A. Taranenko, PoS CFRNC2006 (2006) 021
PHENIX studies of the scaling properties of elliptic flow at RHIC, A. Taranenko, J. Phys. G 34 (2007) S1069-1072

Anisotropic Flow at RHIC – scaling relations

PHENIX studies of the scaling properties of elliptic flow at RHIC,
A. Taranenko, J. Phys. G 34 (2007) S1069-1072





$$m_T = \sqrt{m^2 + p_T^2}$$

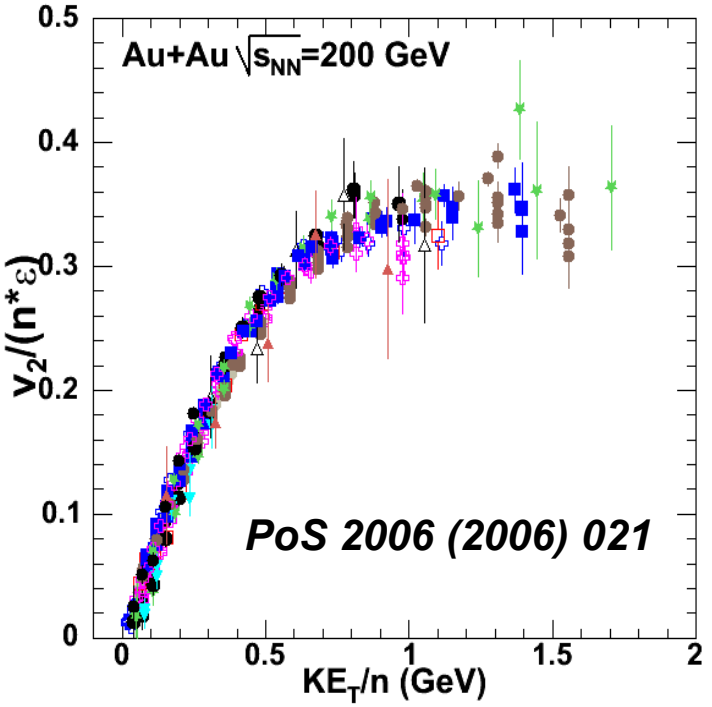
PHENIX (Phys.Rev.Lett.91, Preliminary: QM05, GRC 06)

- $\pi^+ + \pi^-$: min.bias, 0-10%,10-20%,20-30%,30-40%,40-50%,20-60%
- $K^+ + K^-$: min.bias, 0-10%,10-20%,20-30%,30-40%,40-50%,20-60%
- $p + \bar{p}$: min.bias, 0-10%,10-20%,20-30%,30-40%,40-50%,20-60%
- d: min.bias, 10-50%
- ϕ: 20-60%

STAR (Phys. Rev. Lett. 92,Phys. Rev. C 72 (2005), Preliminary QM05, SQM06)

- $\pi^+ + \pi^-$: min.bias
- K^0_S: min.bias, 5-30%,30-70%
- $p + \bar{p}$: min.bias
- $\Lambda + \bar{\Lambda}$: min.bias, 5-30%,30-70%
- $\Xi + \bar{\Xi}$: min.bias
- $\Omega + \bar{\Omega}$: min.bias

$$KE_T = m(\gamma_T - 1) = m_T - m$$



n=2 for mesons and n=3 for baryons

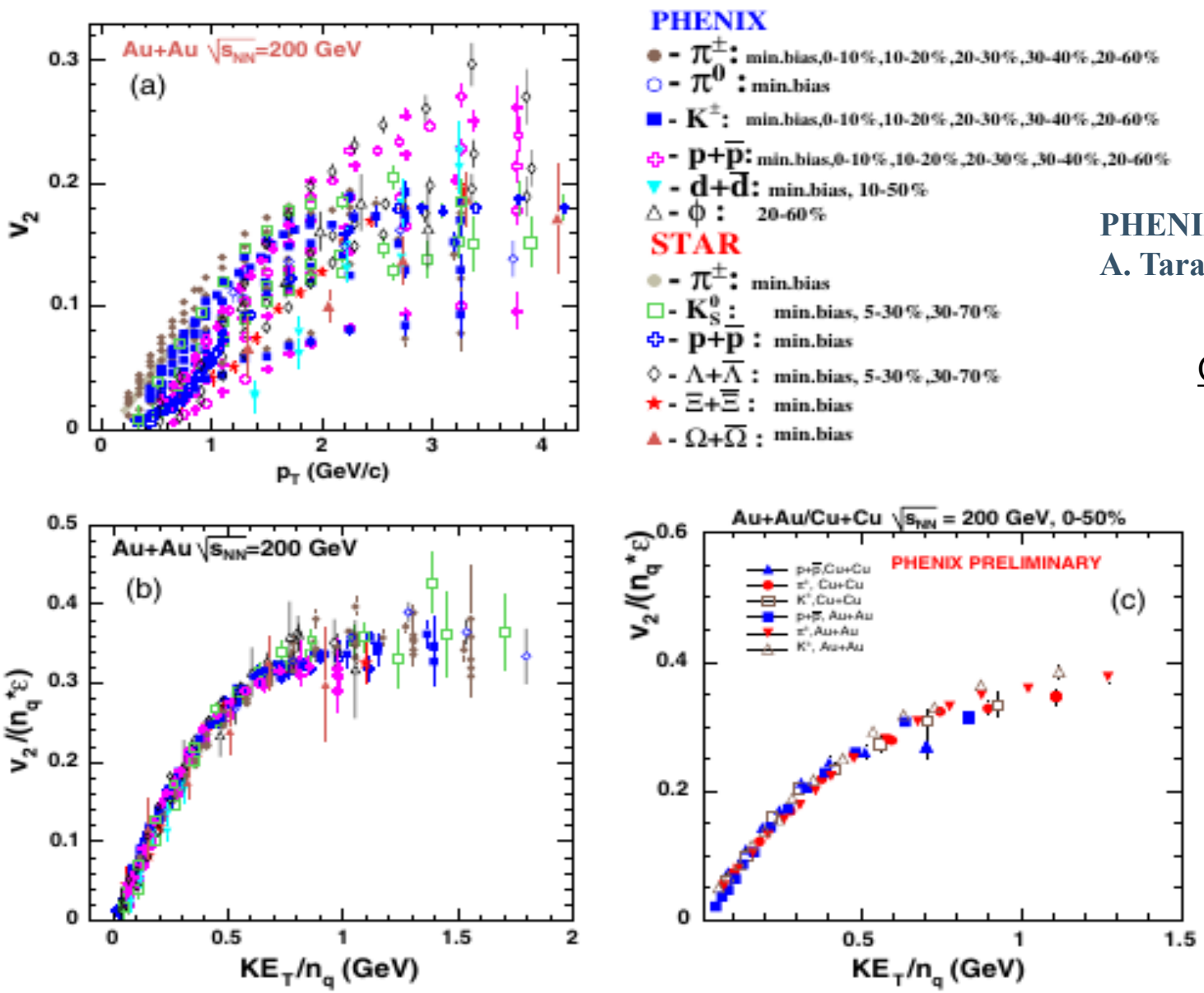


Figure 3. (a) v_2 versus p_T and (b) $v_2/(n_q\epsilon)$ versus KE_T/n_q for several centralities and particle species as indicated. (c) $v_2/(n_q\epsilon)$ versus KE_T/n_q for $\pi^{\pm}$, $K^{\pm}$, and ($\bar{p}$,p) from Cu+Cu and Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV.

PHENIX studies of the scaling properties of elliptic flow at RHIC, A. Taranenko, J. Phys. G 34 (2007) S1069-1072

Quark Matter 2006 (Shanghai, China, 2006 r.),