Коллективные Потоки в Ядро-Ядерных Столкновениях при Энергиях NICA и FAIR

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НИЯУ МИФИ, ИЯИ РАН

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OUTLINE

1) Introduction: V_n measurements

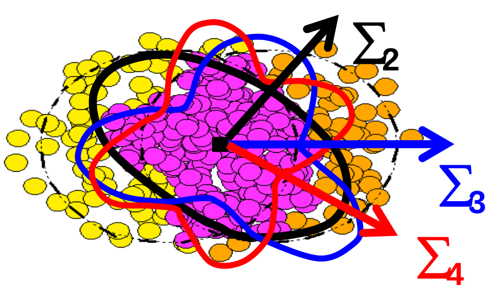
2) RHIC BES: Directed flow (V_1) and EOS

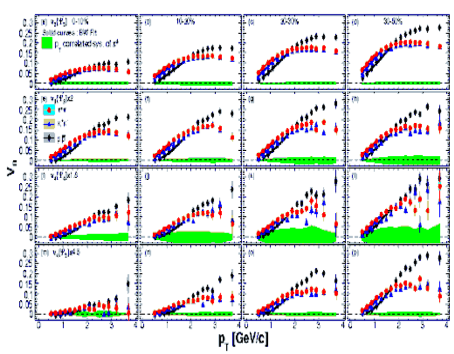
3) RHIC BES: Elliptic (V_2) and Triangular (V_3) flow

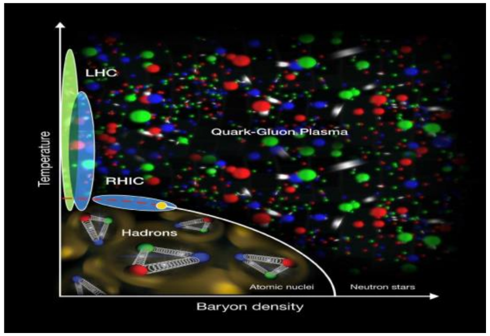
4) Flow measurements at SPS, AGS and SIS18.

5) Outlook for CBM and NICA

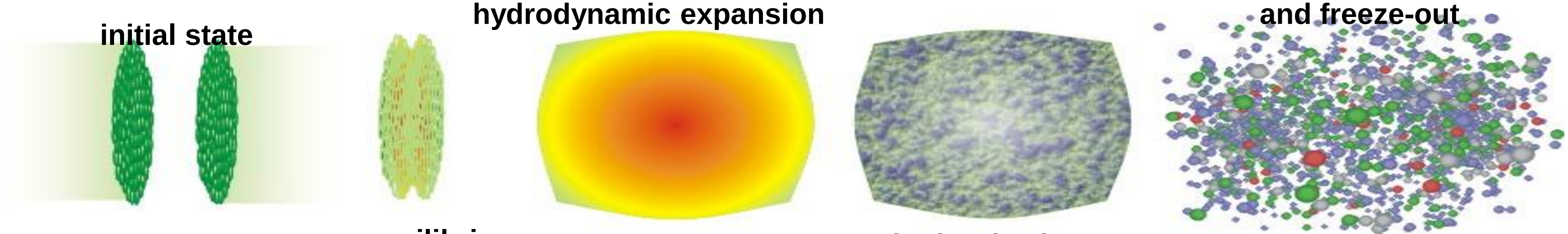
6) Conclusions and Outlook







Relativistic Heavy-Ion Collisions and QGP



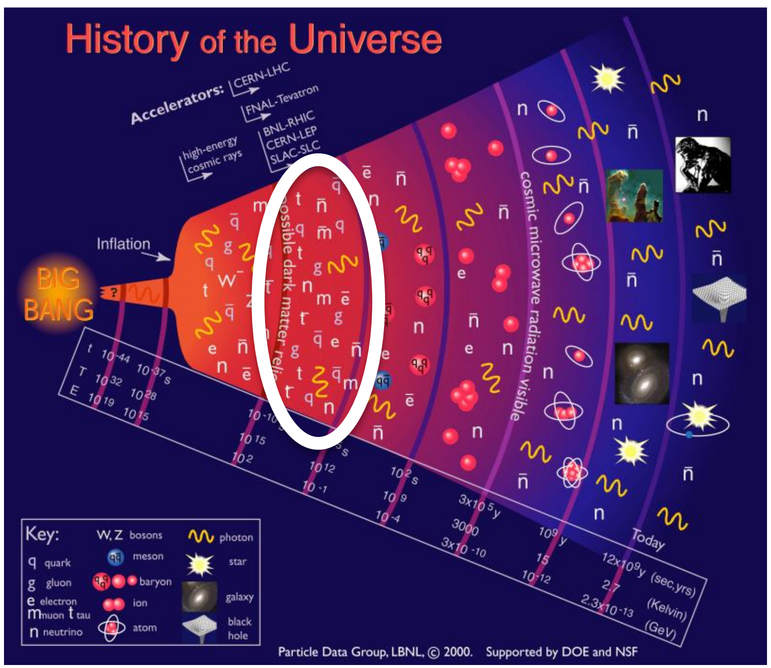
Four good reasons to study the QGP:

It is the primordial form of QCD matter at high temperature or baryon density.

It was present during the first few microseconds of the Big Bang.

It provides an example of phase transitions which may occur at a variety of higher temperature scales in the early universe.

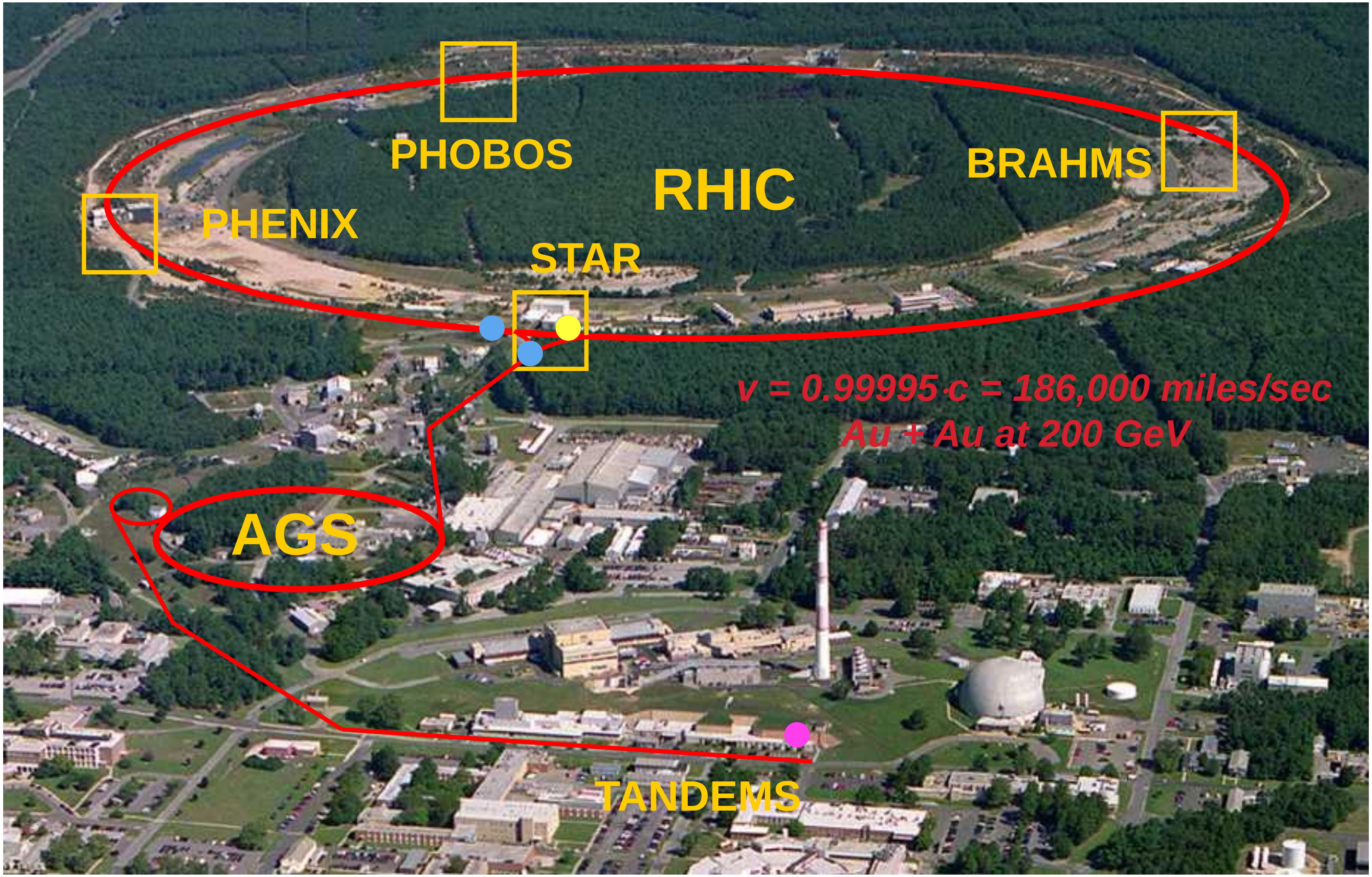
It can provide important insights on the origin of mass for matter, and how quarks are confined into hadrons.



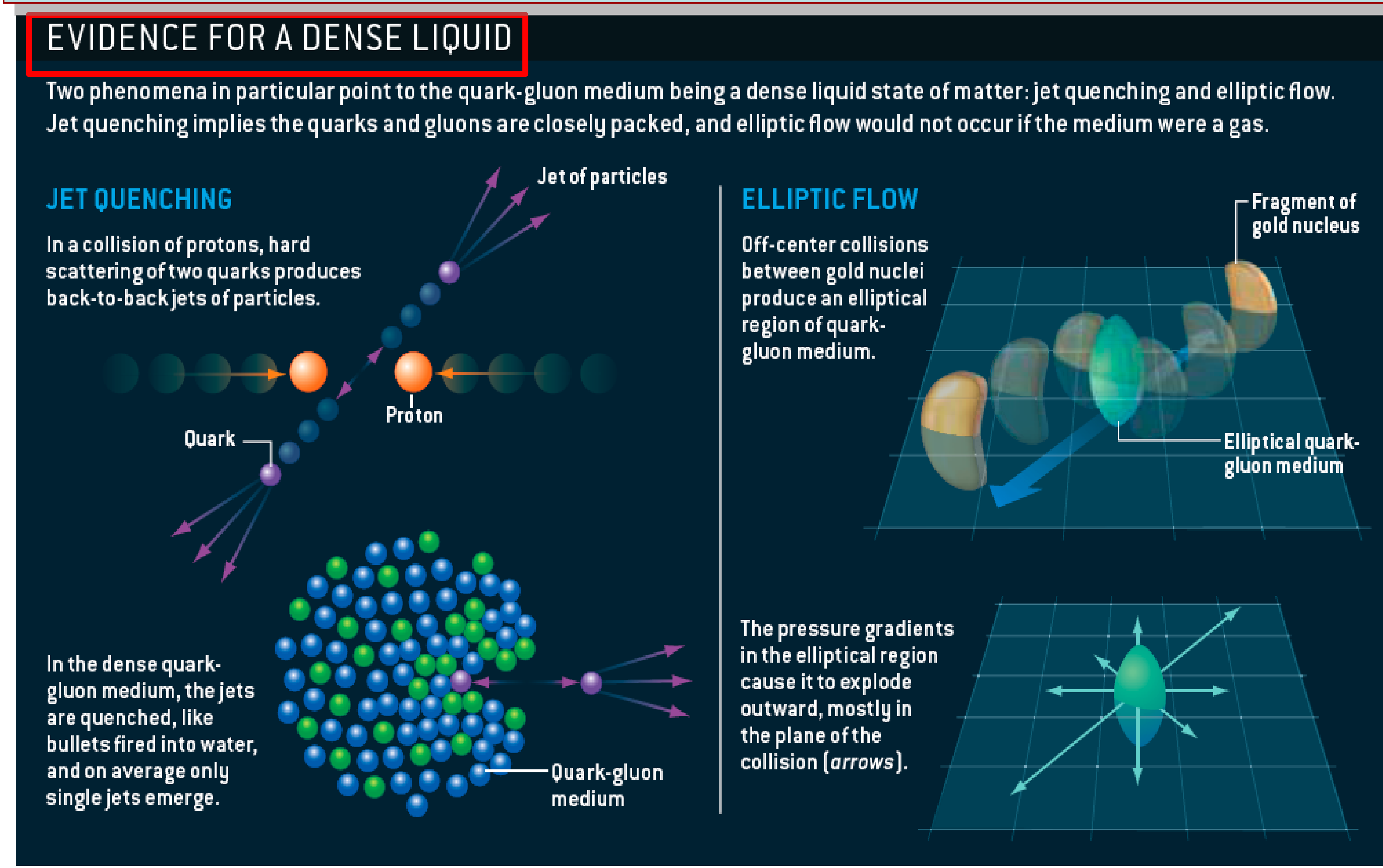
Gyulassy, Nucl. Phys. A750, 30-63, 2005

Discovery of Quark-Gluon Plasma

Relativistic Heavy-Ion Collider (BNL), Upton, NY (USA)



The QGP Discovered at RHIC: 2005-2006



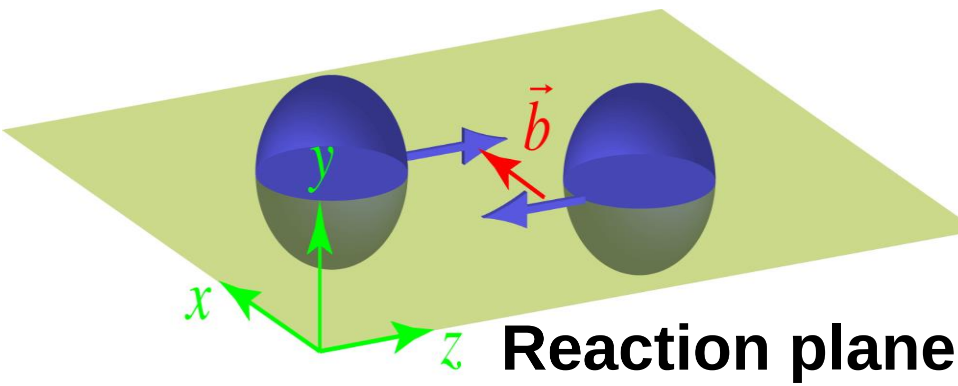
M. Roirdan and W. Zajc, Scientific American, May 2006

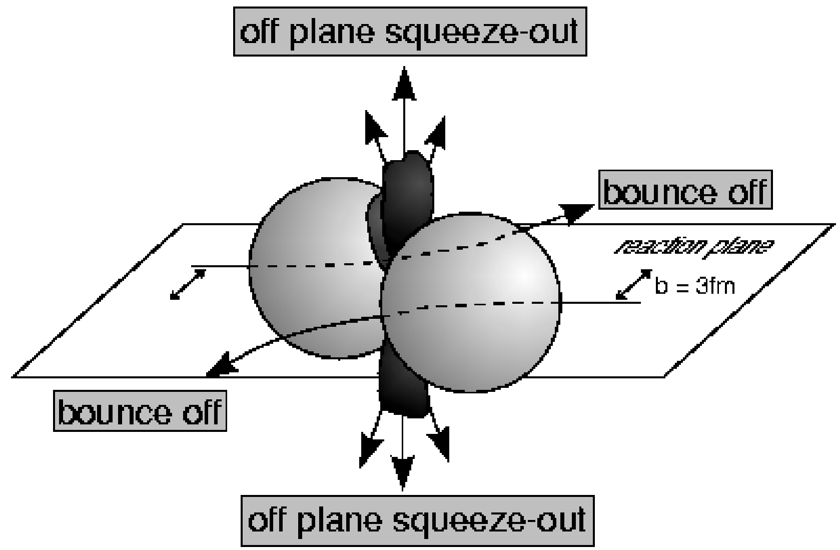
“Squeeze-Out” - First Elliptic Flow Signal in HIC

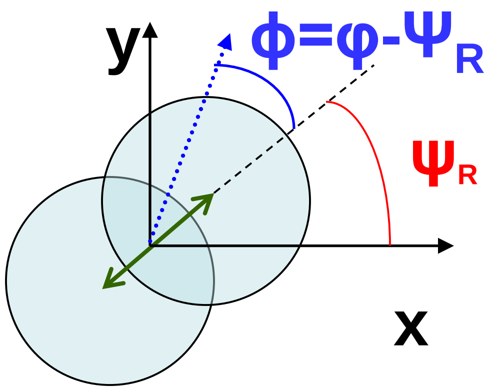
1989

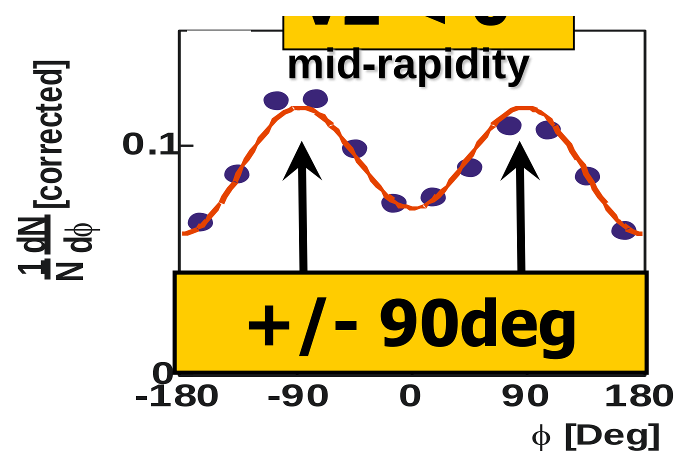
Diogene, M. Demoulins et al., Phys. Lett. B241, 476 (1990)

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









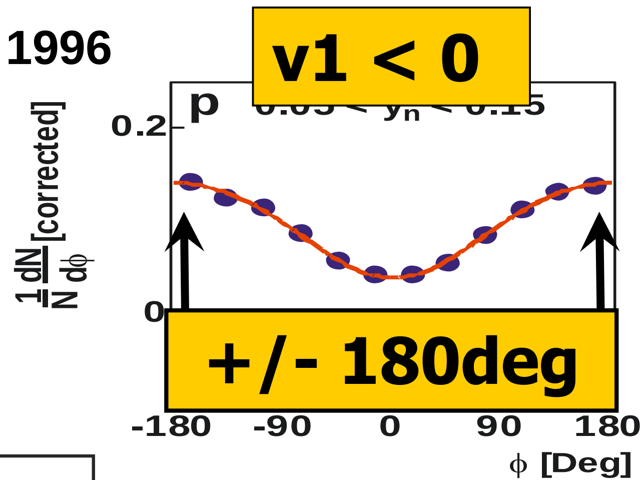
Fourier decomposition of single particle (semi) inclusive spectra:

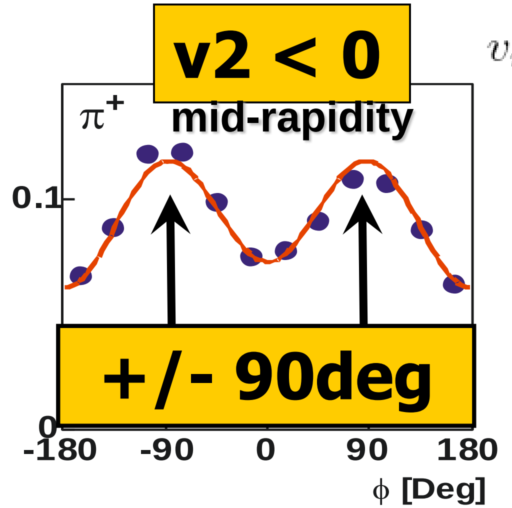
$$\frac{d^3N}{dp_t\,dy\,d\varphi} = \frac{d^2N}{dp_t\,dy}\frac{1}{2\pi}\left(1 + 2v_1\cos(\varphi) + 2v_2\cos(2\varphi) + \ldots\right)$$

Directed flow

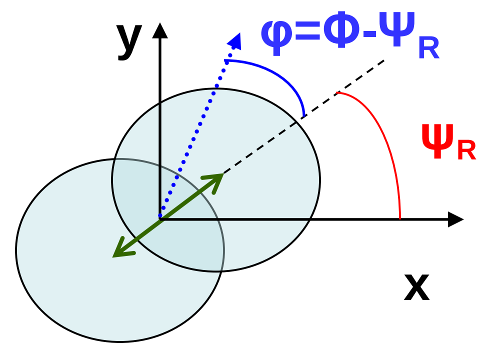
Elliptic flow

KAOS 1996





$v_n = < cos(n[\phi - \Phi_R]) >$



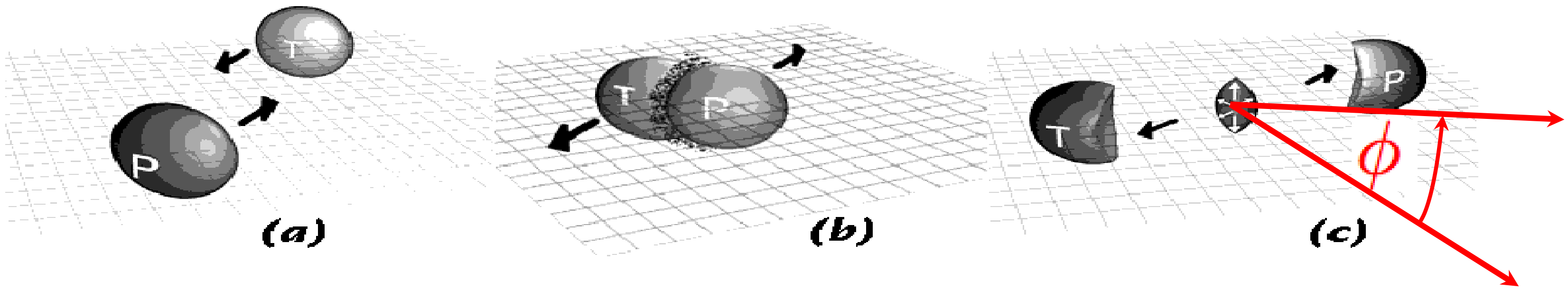
1996

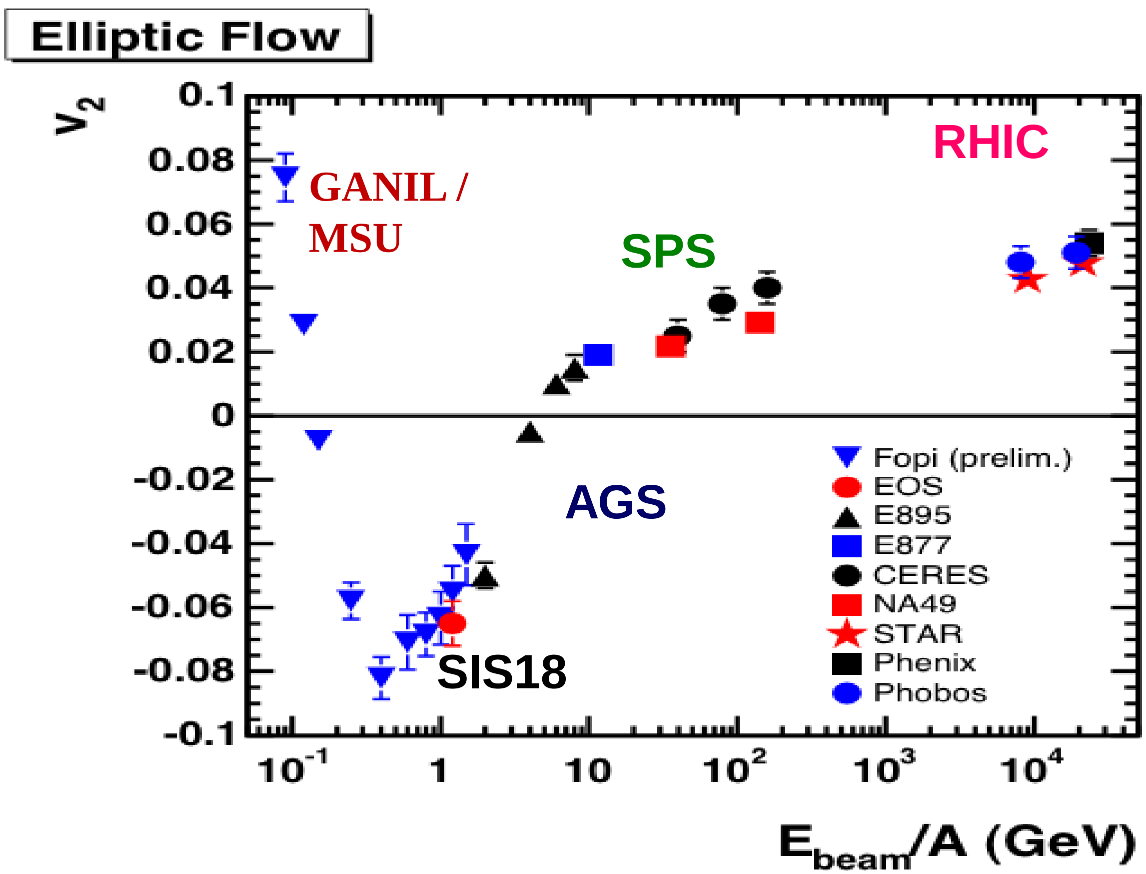
Sergei Voloshin, Y. Zhang, Z. Phys. C70,(1996), 665

Sin terms are skipped by symmetry arguments: It is equally probable for a particle to be produced in directions ϕ and $-\phi$: $\sin(n\phi)+\sin[n(-\phi)]= \sin(n\phi)-\sin(n\phi)=0$

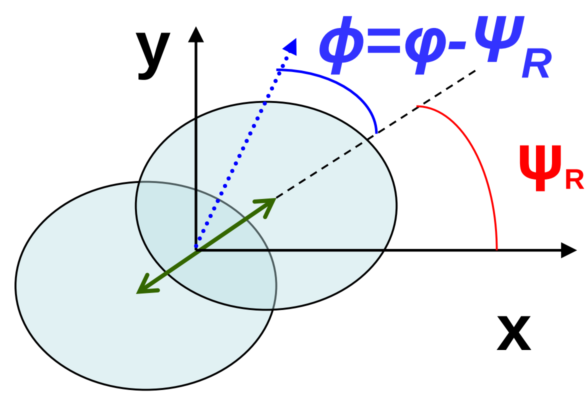
For a symmetric system (AuAu, CuCu) and ideal geometry at y=0, v_{odd} vanishes: it is equally probable for a particle to be produced in directions ϕ and $\phi + \pi$:

Elliptic Flow Measurements 1989-2002



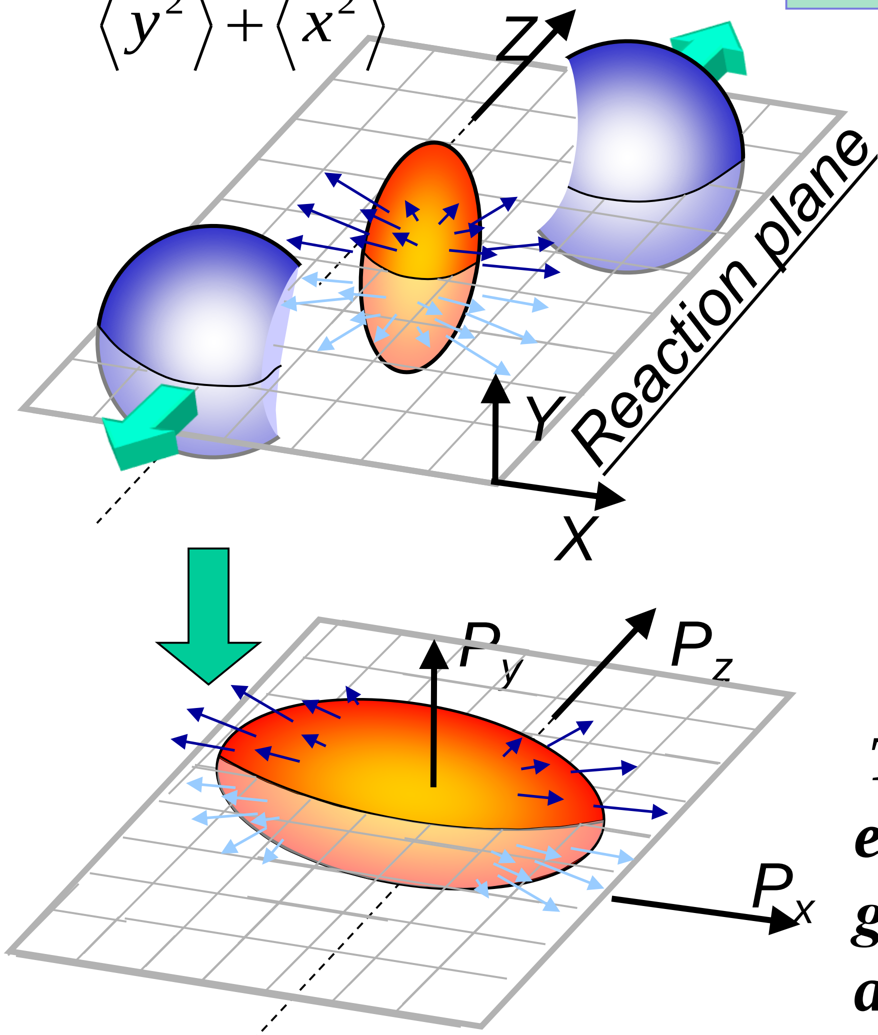


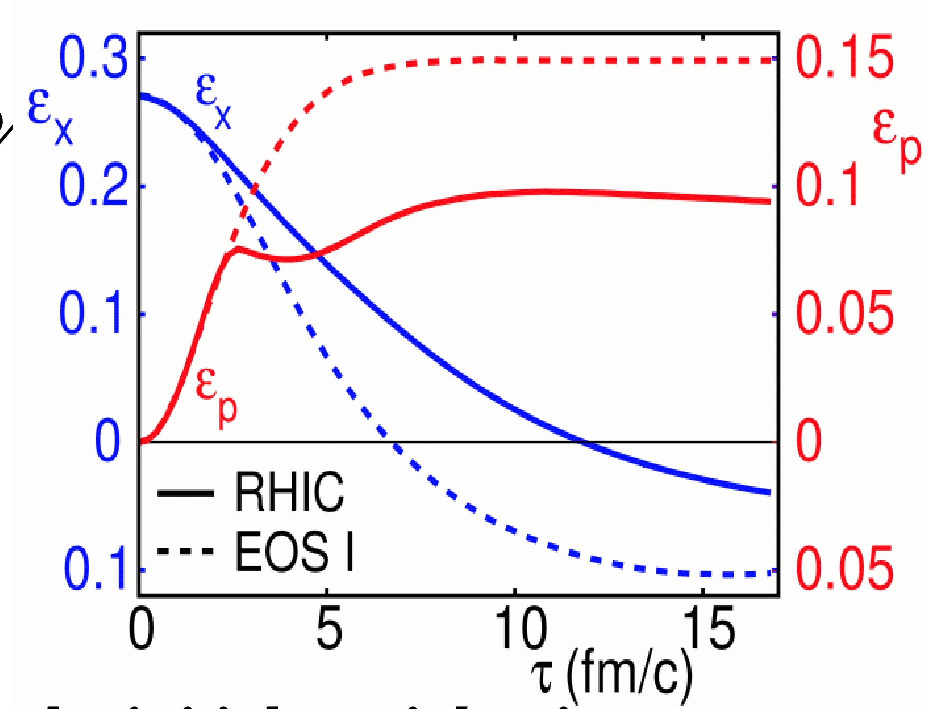
$$\frac{dN}{df} \mu \left[1 + 2v_2 \cos(2f)\right]$$



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

Elliptic Flow at RHIC





The initial spatial anisotropy evolves (via interactions and density gradients) → Momentum-space anisotropy

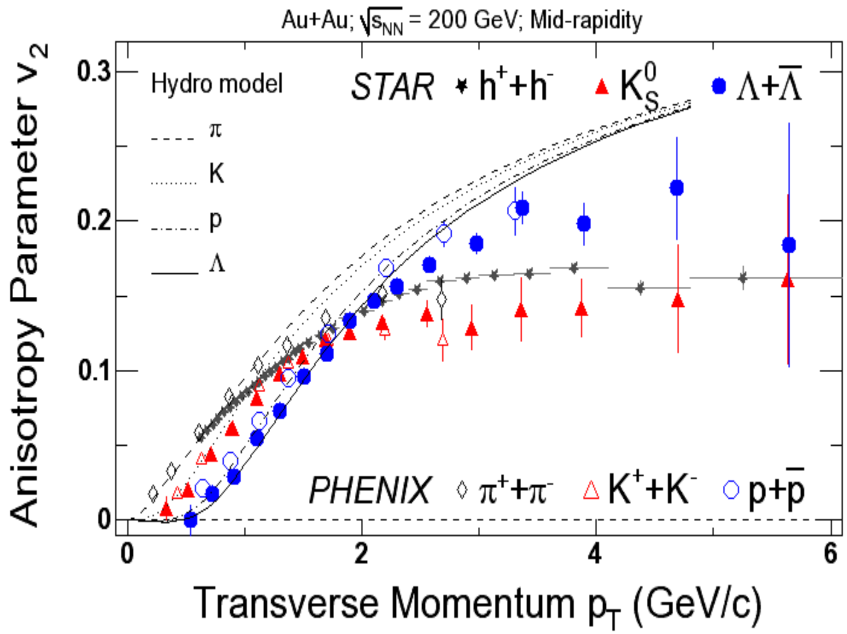
Signal is self-quenching with time

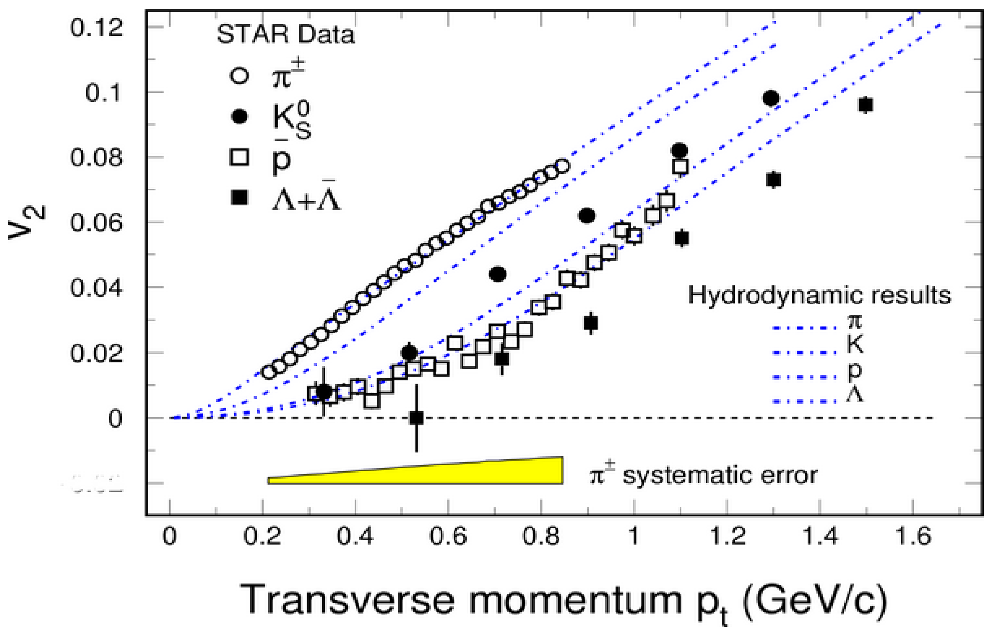
$$v_2 = \frac{\langle p_x^2 \rangle - \langle p_y^2 \rangle}{\langle p_x^2 \rangle + \langle p_y^2 \rangle}$$

$$\boxed{v_2 = \langle \cos(2[\varphi - \Psi_R]) \rangle}$$

Elliptic Flow at RHIC – signal of sQGP (2005-2006)

STAR : PRC 72, 014904 (2005)



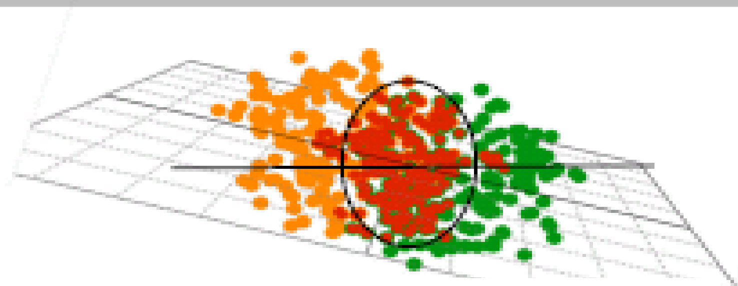


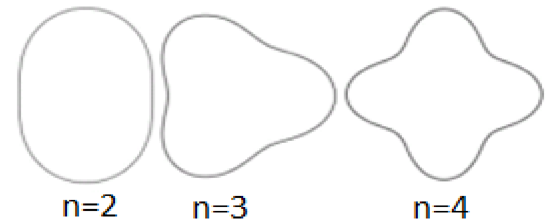
For p_T < 2.0 GeV/c $V_2(p_T)$ and p_T spectra of identified hadrons are in a good agreement with the predictions of ideal relativistic hydrodynamics (rapid thermalization t< 1fm/c and an extremely small η/s)

Flavor dependence of v2(pT) enters mainly through mass of the particles → in hydro all particles flow with a common velocity !!!

p_T< 2.0 GeV/c (~ 98% of all produced particles)

2011: Anisotropic Flow at RHIC/LHC





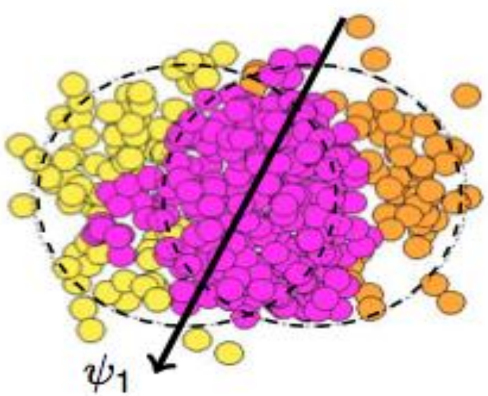
$$\epsilon_n = \sqrt{\frac{\langle r^n \cos n\phi\rangle + \langle r^n \sin n\phi\rangle}{\langle r^n\rangle}}$$

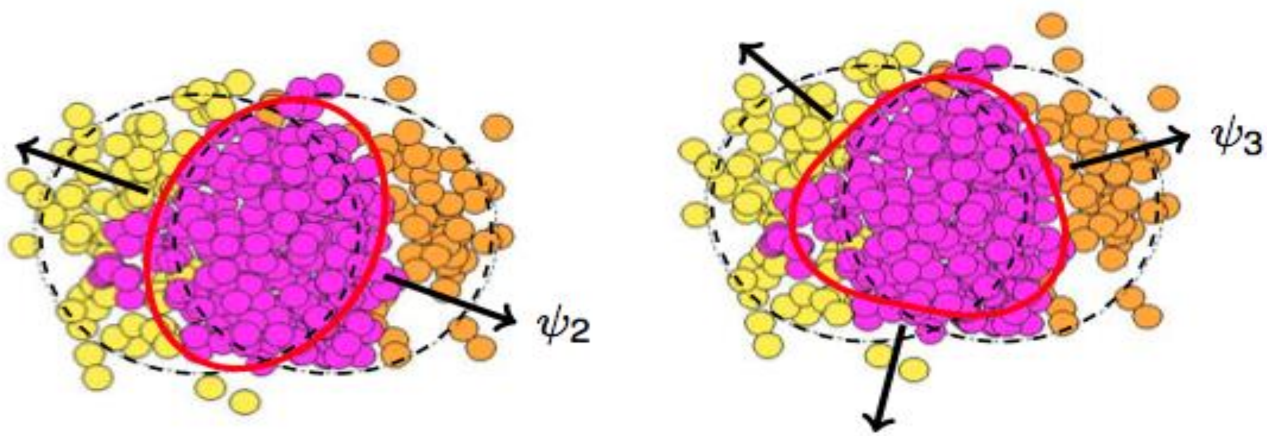
$$\frac{dN}{d\phi} \propto \left(1 + 2\sum_{n=1} v_n \cos\left[n\left(\phi - \Psi_n\right)\right]\right)$$

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

For *smooth profile* $\varphi \rightarrow \varphi + \pi$

Odd harmonics = 0

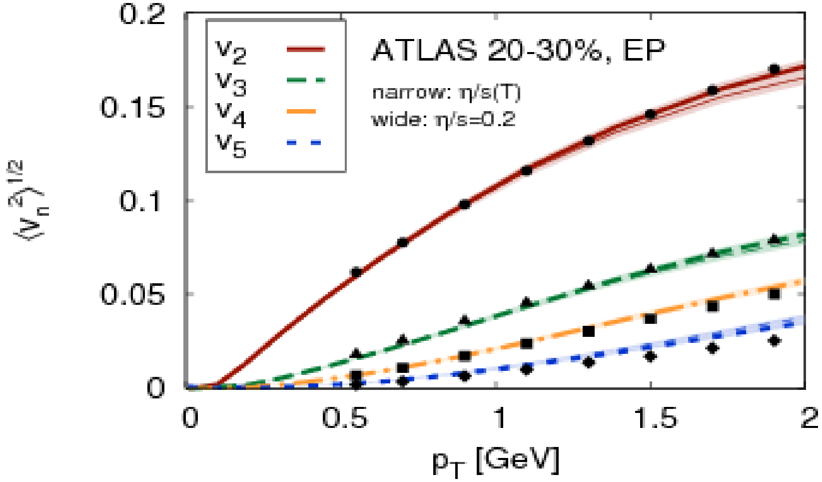


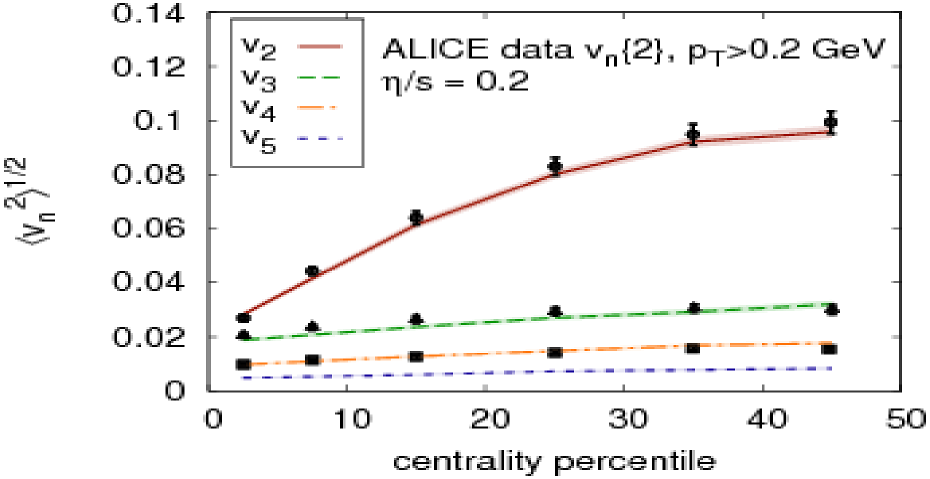


For "lumpy" *profile* $\varphi \neq \varphi + \pi$

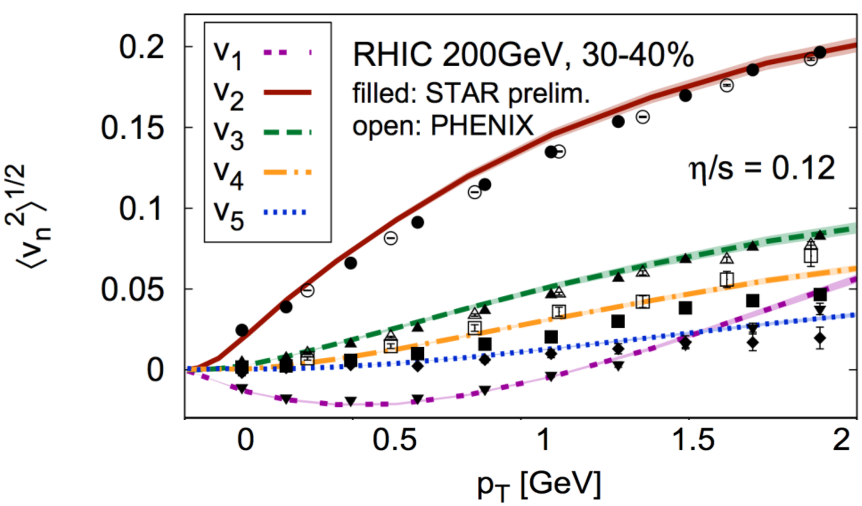
Odd harmonics $\neq$ 0

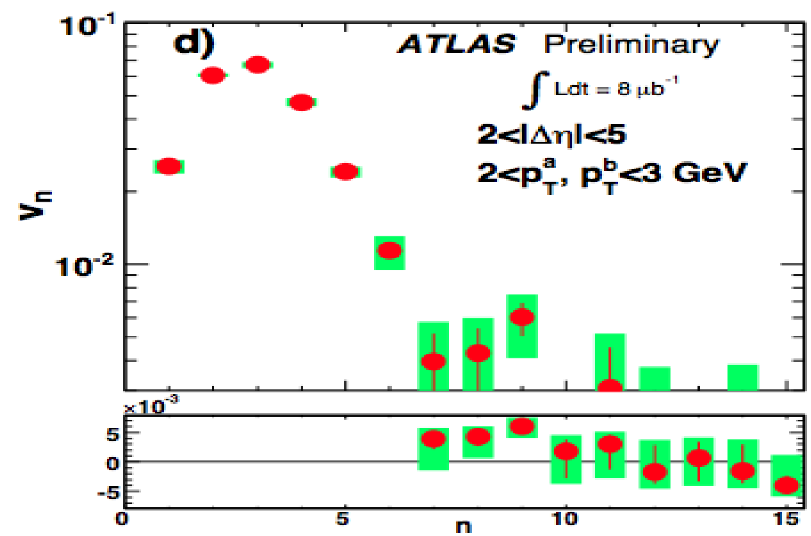
Anisotropic Flow at RHIC/LHC – data vs models



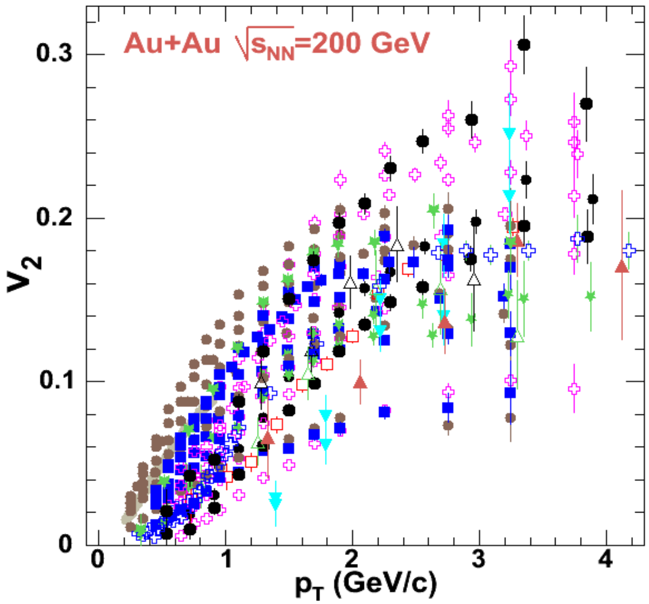


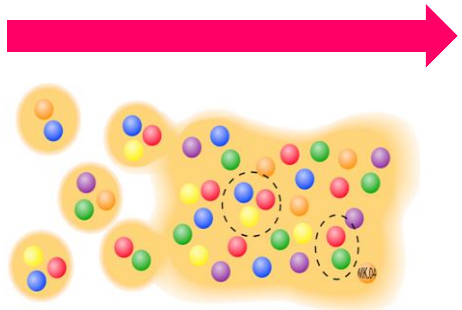
Gale, Jeon, et al., Phys. Rev. Lett. 110, 012302



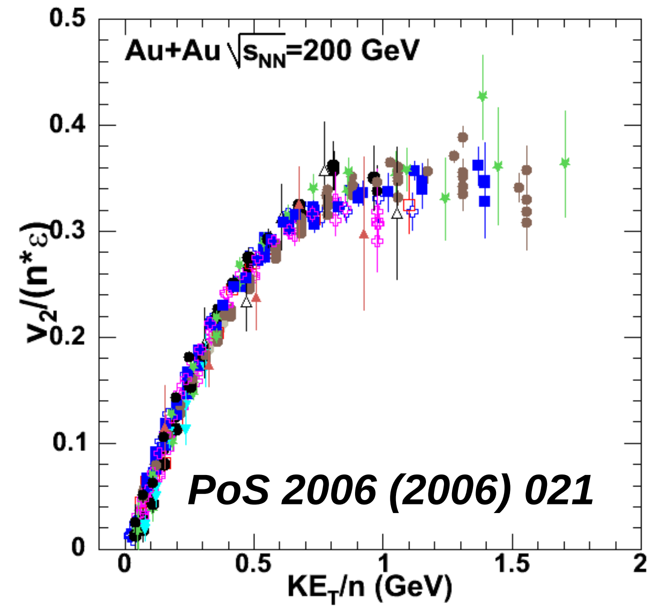


Anisotropic Flow at RHIC/LHC – scaling relations

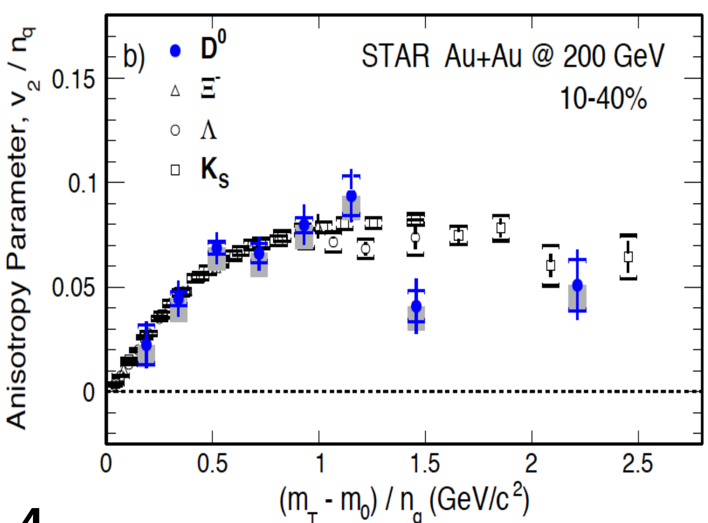




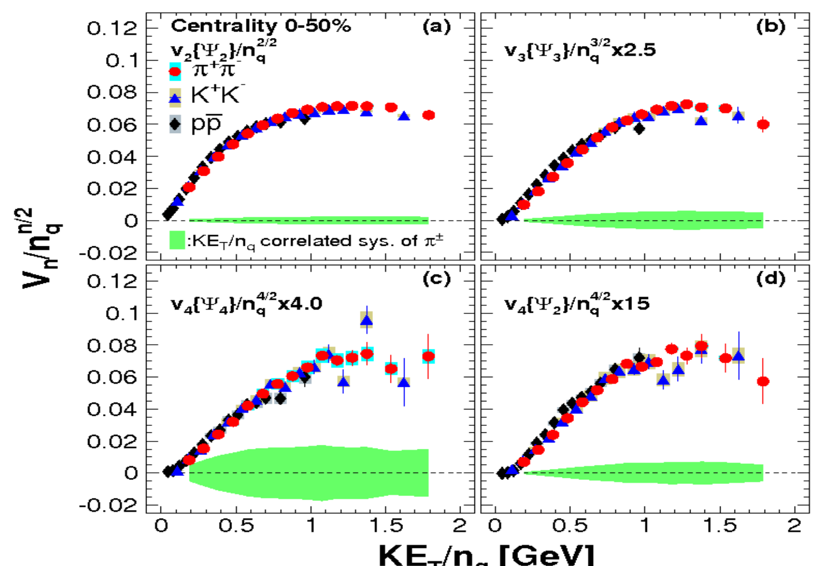
n=2 for mesons
and
n=3 for baryons



PRL118 (2017) 212301

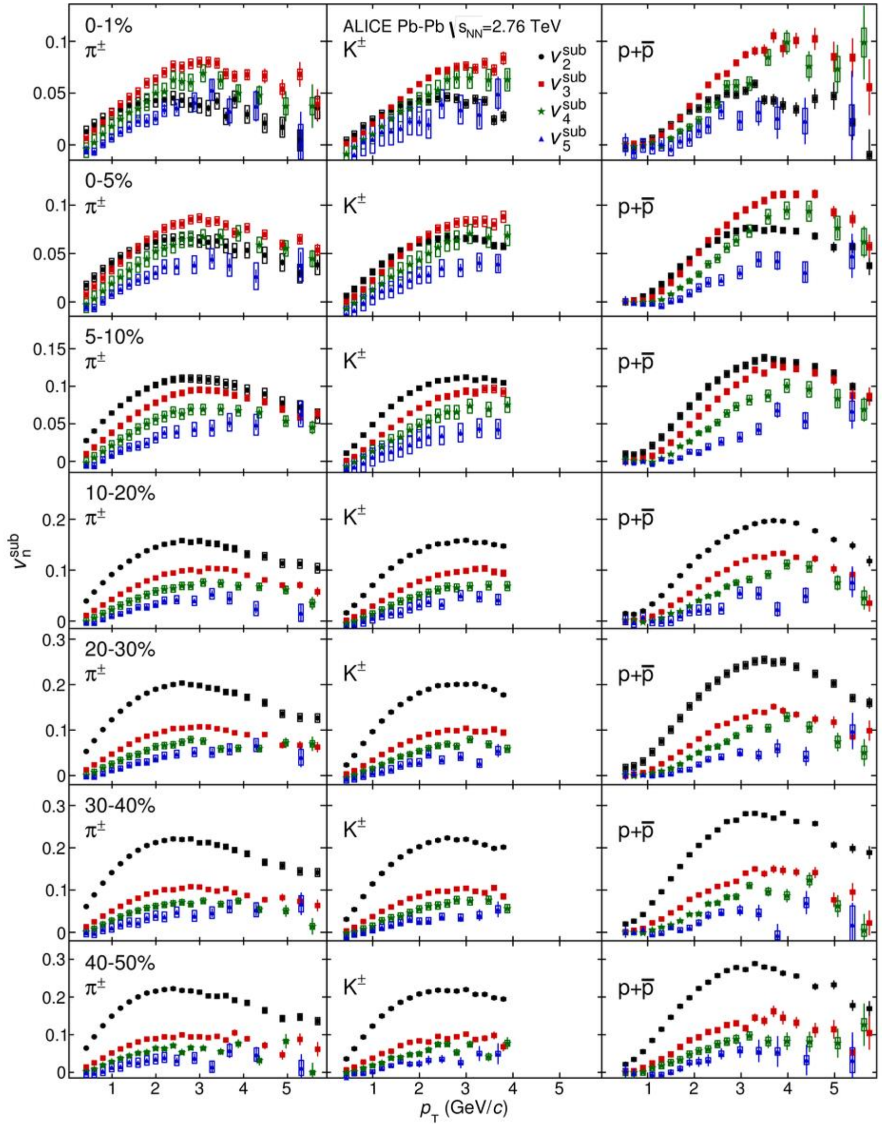


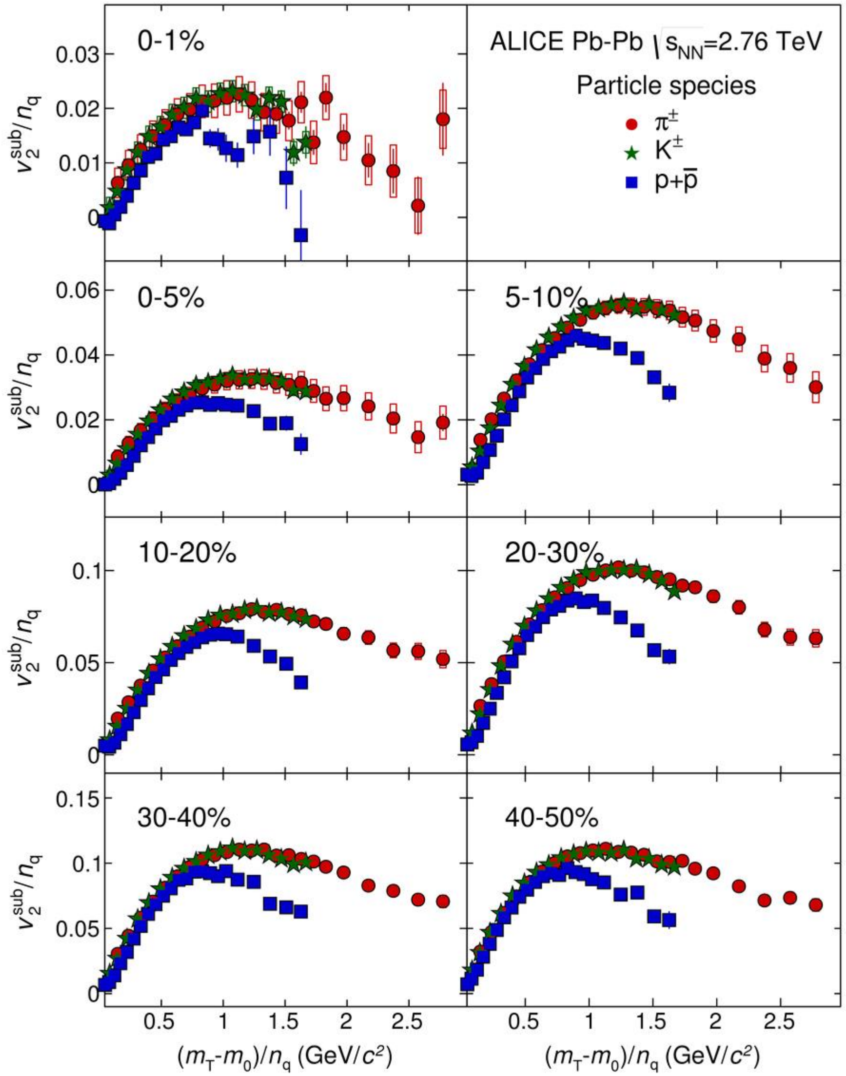
Phys. Rev.C.93.051902(R)



Flow is partonic @ LHC

Alice - arXiv:1606.06057





KE_T & $\left(n_q\right)^{n/2}$ scaling validated for v_n → Partonic flow

Different methods, non-flow, fluctuations

How fluctuations affect the measured values of v_n: $\sigma^2_{v_n} = \langle v_n^2 \rangle - \langle v_n \rangle^2$ - magnitude of flow flutuations
The effect of the fluctuations on v_n estimates can be obtained from

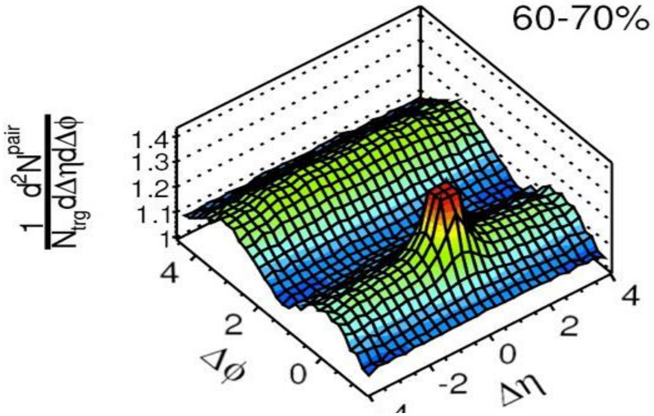
$$\langle v_n^2 \rangle = \bar{v}_n^2 + \sigma^2_{v_n},$$
$$\langle v_n^4 \rangle = \bar{v}_n^4 + 6\sigma^2_{v_n}\bar{v}_n^2,$$
$$\langle v_n^6 \rangle = \bar{v}_n^6 + 15\sigma^2_{v_n}\bar{v}_n^4, \quad (1)$$

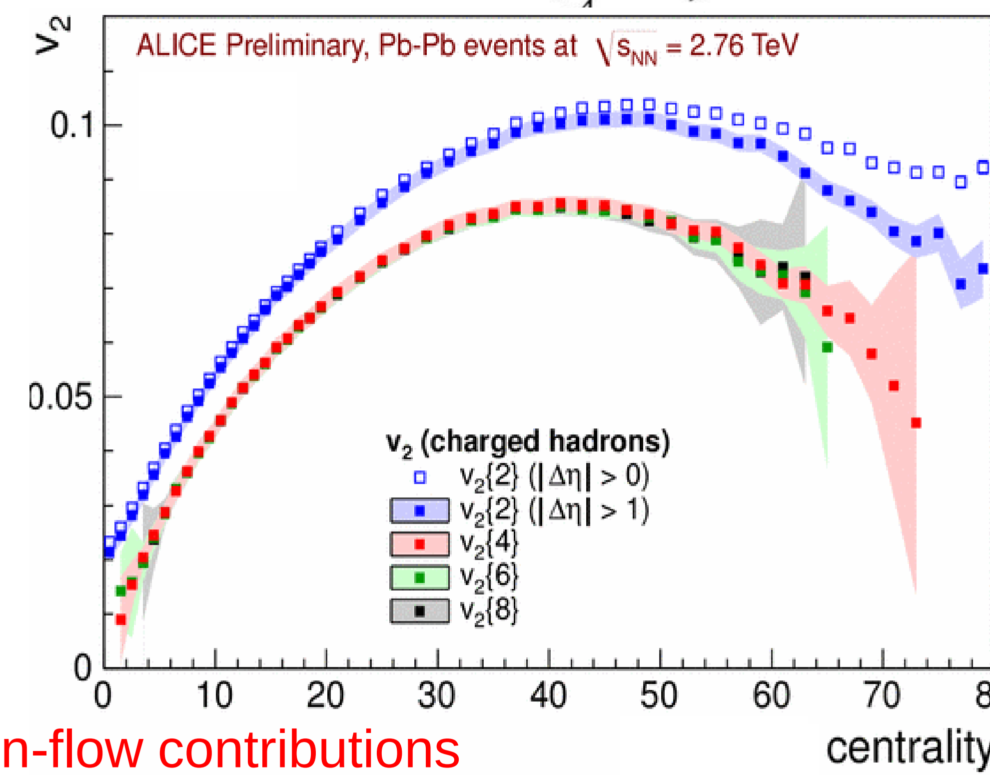
$$v_n\{2\} = \sqrt{\langle v_n^2 \rangle},$$
$$v_n\{4\} = \sqrt[4]{2\langle v_n^2 \rangle^2 - \langle v_n^4 \rangle},$$
$$v_n\{6\} = \sqrt[6]{\frac{1}{4}\left(\langle v_n^6 \rangle - 9\langle v_n^2 \rangle\langle v_n^4 \rangle + 12\langle v_n^2 \rangle^3\right)}. \quad (2)$$

Here we have introduced the notation $v_n\{k\}$ as the flow estimate from the cumulant $c_n\{k\}$. In case that $\sigma_{v_n} \ll \bar{v}_n$ we obtain, up to order $\sigma^2_{v_n}$:

$$v_n\{2\} = \bar{v}_n + \frac{1}{2}\frac{\sigma^2_{v_n}}{\bar{v}_n},$$
$$v_n\{4\} = \bar{v}_n - \frac{1}{2}\frac{\sigma^2_{v_n}}{\bar{v}_n},$$
$$v_n\{6\} = \bar{v}_n - \frac{1}{2}\frac{\sigma^2_{v_n}}{\bar{v}_n}. \quad (3)$$

The difference between $v_n\{2\}$ and $v_n\{4\}$ is sensitive to not only nonflow but also to the event-by-event v_n fluctuations.



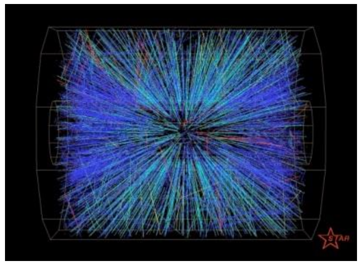


Requires the suppression of non-flow contributions

(**HBT, Jets & di-jets, Res. Decay, Mom. Consrv.**)

Flow Measurements at RHIC with STAR/PHENIX

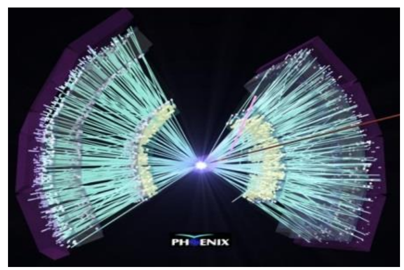
ZDC/SMD FTPC TPC FTPC ZDC/SMD



STAR

$|\eta| < 1.0$ $\quad$ $2.5 < |\eta| < 4.0$ $\quad$ $|\eta| > 6.3$ $\quad$ η

comparison



ZDC/SMD BBC/MPC Central Arms BBC/MPC ZDC/SMD

RXN RXN

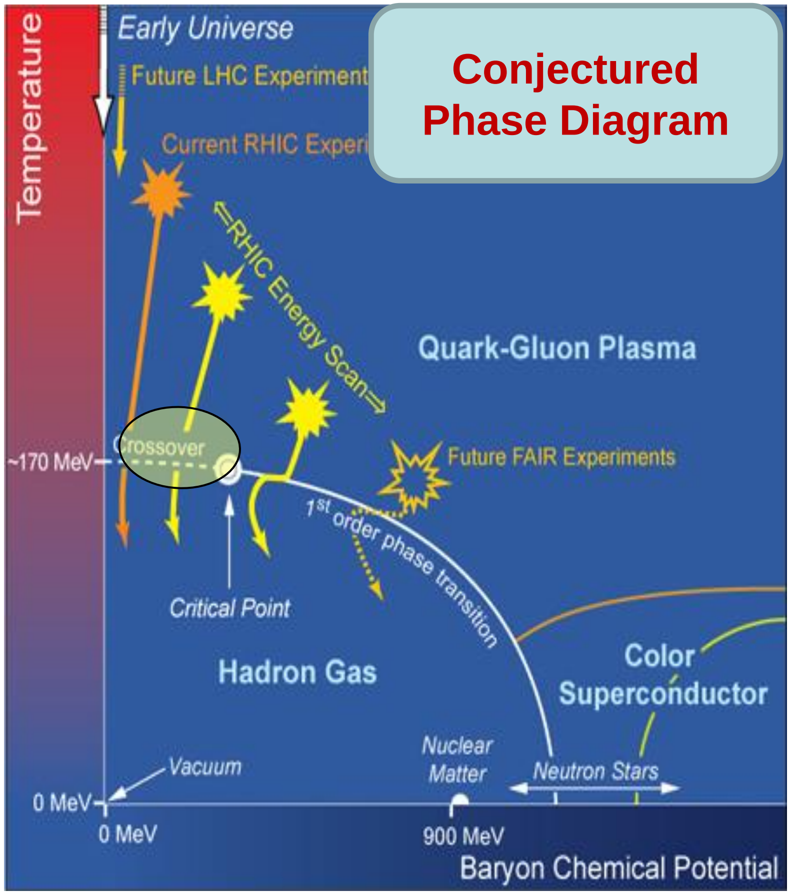
η

PHENIX

$|\eta| < 0.35$ $\quad$ $1.0 < |\eta| < 2.8$ $\quad$ $3.1 < |\eta| < 3.7$ $\quad$ $3.1 < |\eta| < 3.9$ $\quad$ $|\eta| > 6.6$

2012- FVTX $1 < |\eta| < 3$

Quantitative study of the QCD phase diagram



Validation of the crossover transition leading to the sQGP

→ **Necessary requirement for CEP**

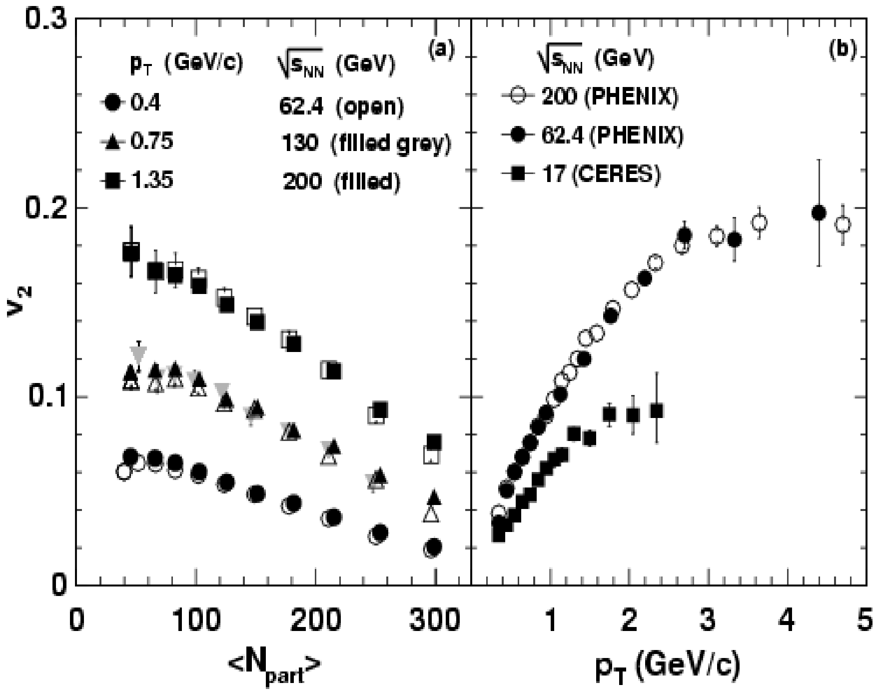
Strategy for RHIC BES1:

- **Map turn-off of QGP signatures**
- **Location of the Critical End Point (CEP)?**
- **Location of phase coexistence regions?**
- **1st order phase transition signs**
- **Detailed properties of each phase?**

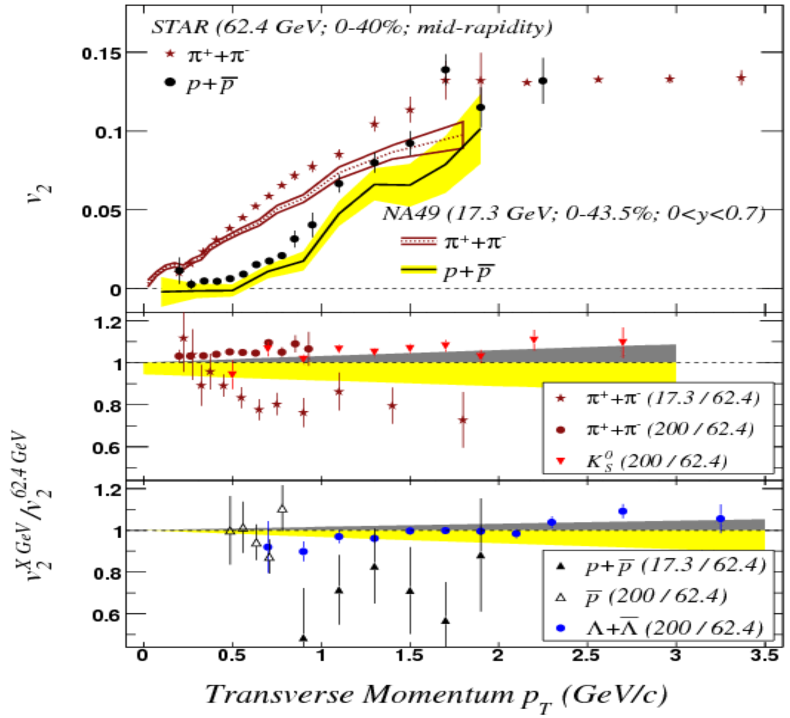
$$\frac{\eta}{s}(T,\mu),\ \frac{\zeta}{s}(T,\mu),\ c_s(T),\ \hat{q}(T),\ \alpha_s(T),\ \text{etc}$$

Beam Energy dependence of V_2 : before 2010

Phenix: Phys. Rev. Lett. 94, 232302 (2005)

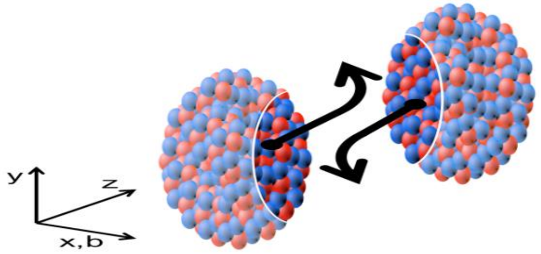


STAR: Phys.Rev.C75:054906,2007

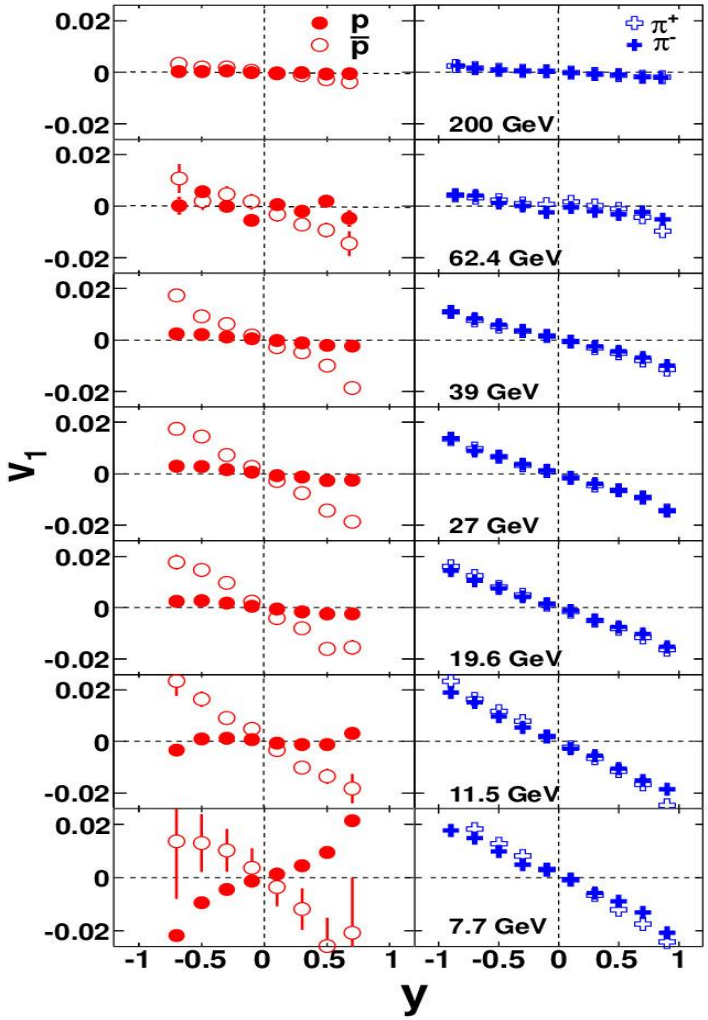


- *Saturation of differential elliptic flow at 62.4–200 GeV (STAR/PHENIX)*
- *PHENIX: RHIC/SPS: ~ 50% difference . STAR: RHIC/SPS ~ 10-15% difference in the differential flow results !*
- *2011: New measurements at RHIC (BES program) and LHC !*

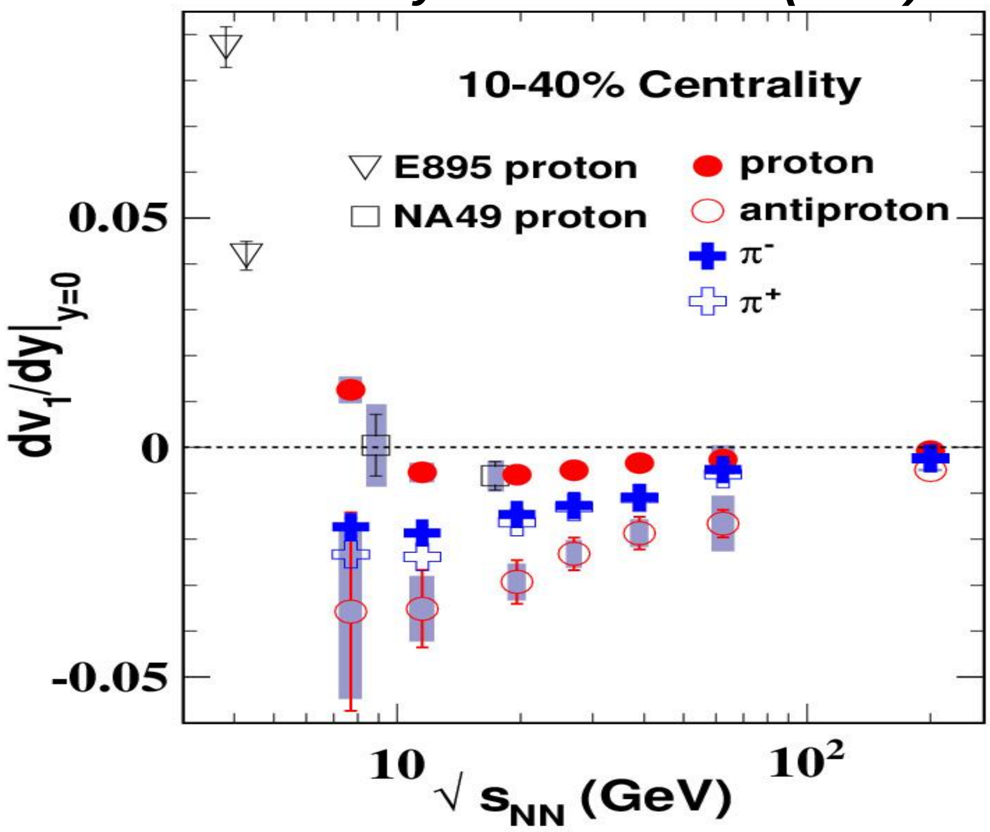
Beam Energy Dependence of Directed Flow (v_1)



- *Generated during the nuclear passage time ($2R/\gamma$) – sensitive to EOS*
- *RHIC 200 GeV ($2R/\gamma$) ~ 0.1 fm/c*
- *AGS: 3-4.5 GeV ($2R/\gamma$) ~ 9-5 fm/c*

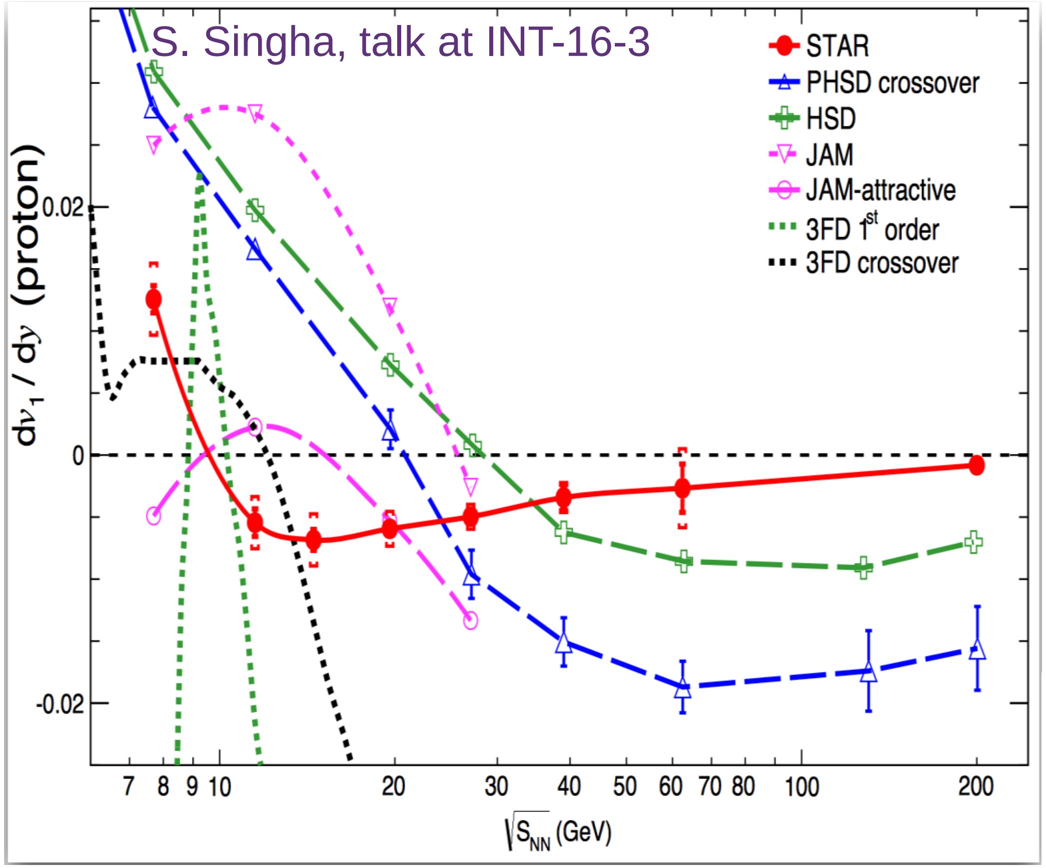


STAR: Phys.Rev.Lett. 112 (2014)



Trend observed by STAR inline with NA49 and E895 data

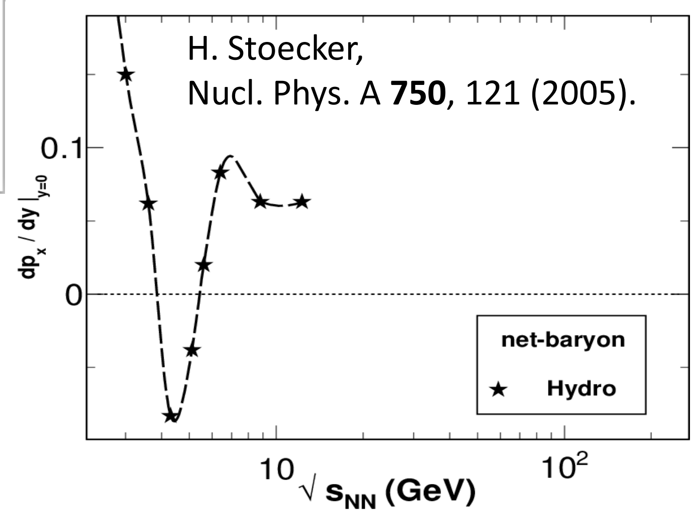
Beam Energy Dependence of Directed Flow (v_1)



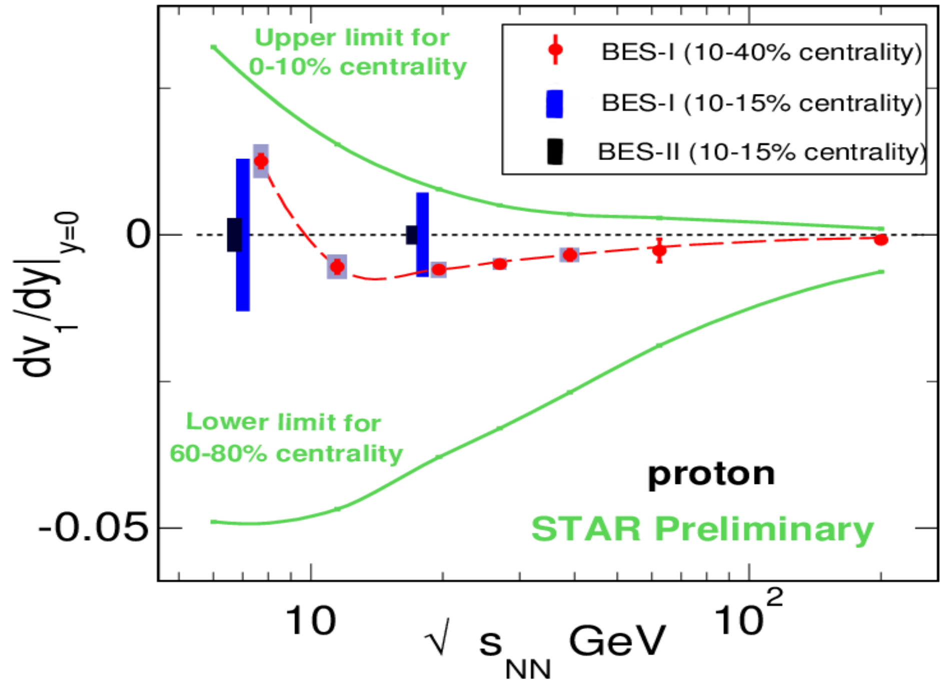
Minimum in slope of directed flow (dv_1/dy) as a function of beam energy for baryons may suggest sudden softening of EOS - sign of the 1st order phase transition

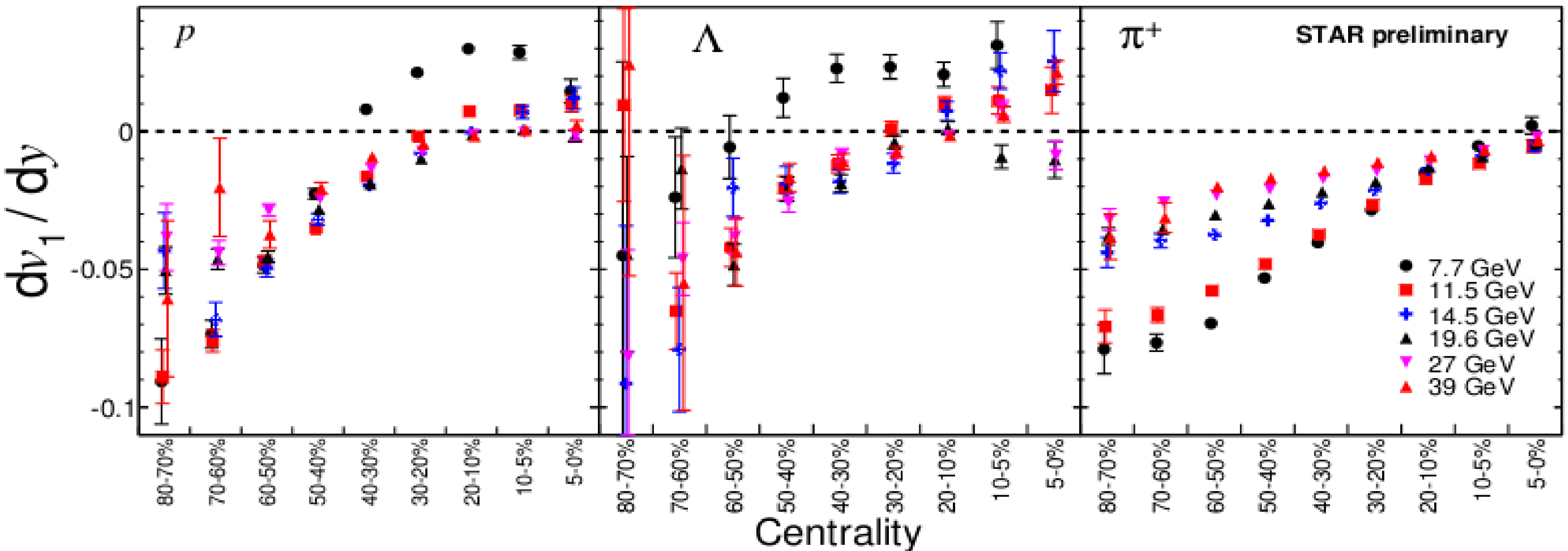
Proton v_1 probes interplay of baryon transport and hydro behavior

None of the models explains the data
• Systematics associated with the models is quite large



Centrality Dependence of Directed Flow (v_1)

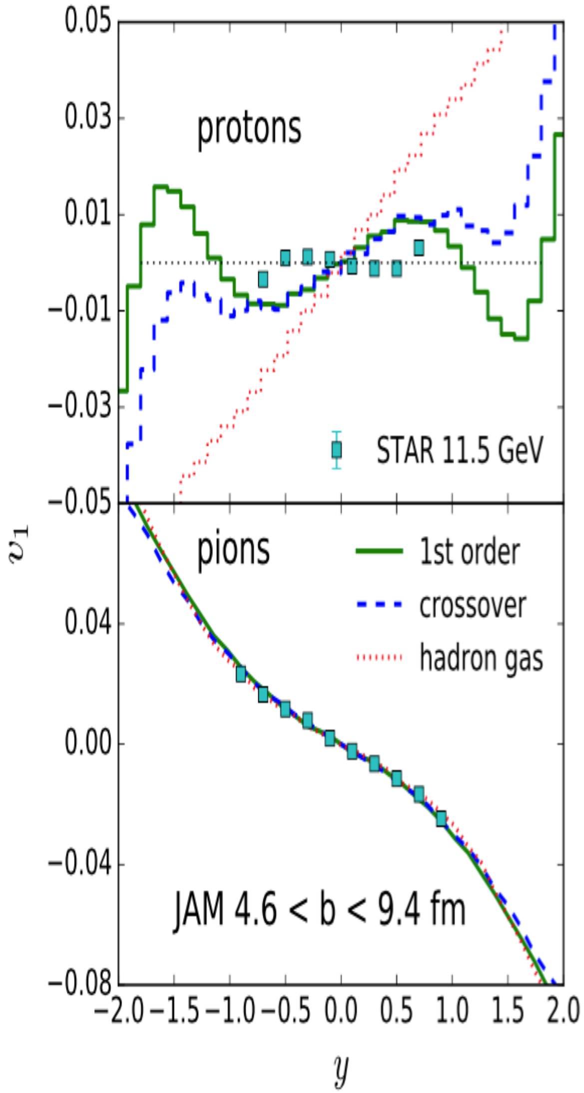


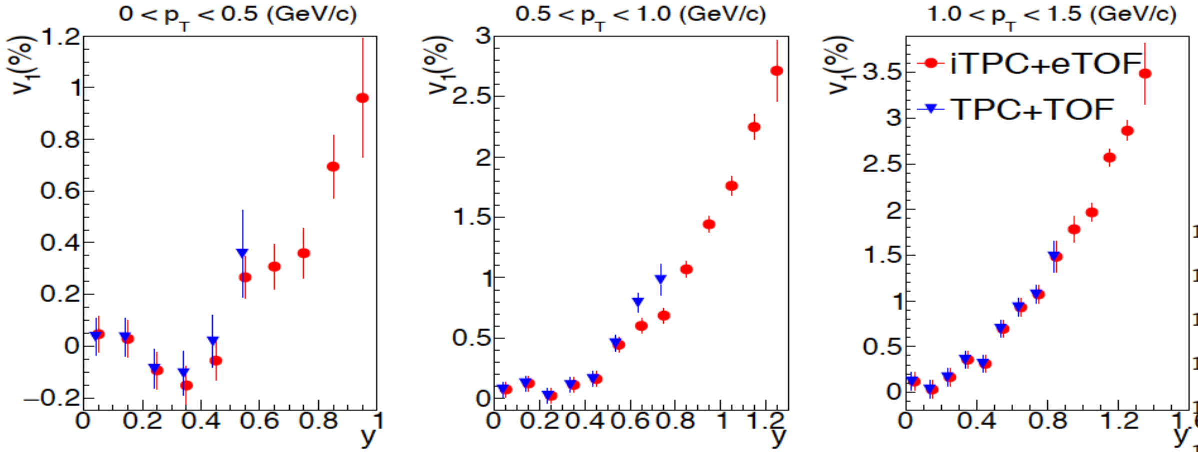


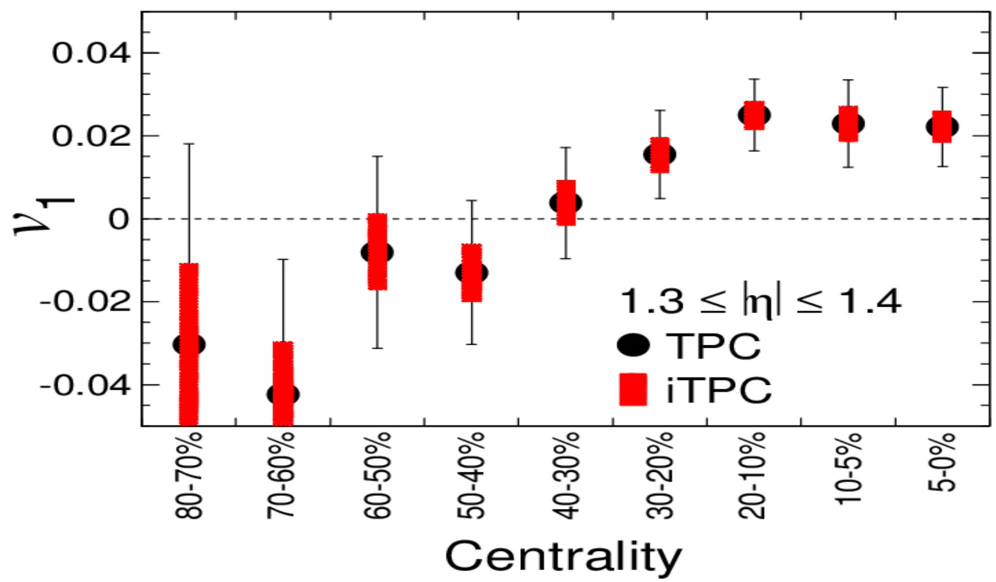
Prospects for directed flow measurements: STAR BES2

Phys.Rev. C94 (2016)

arXiv:1609.05100

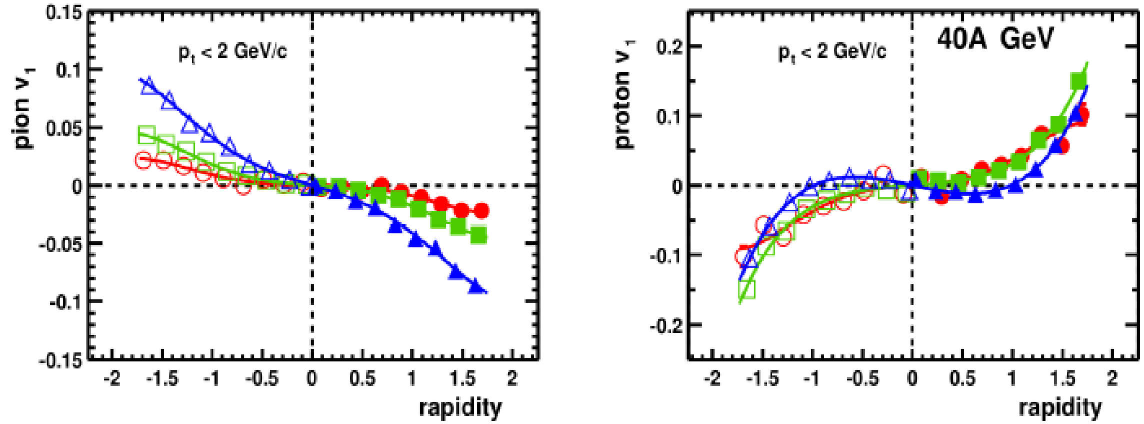


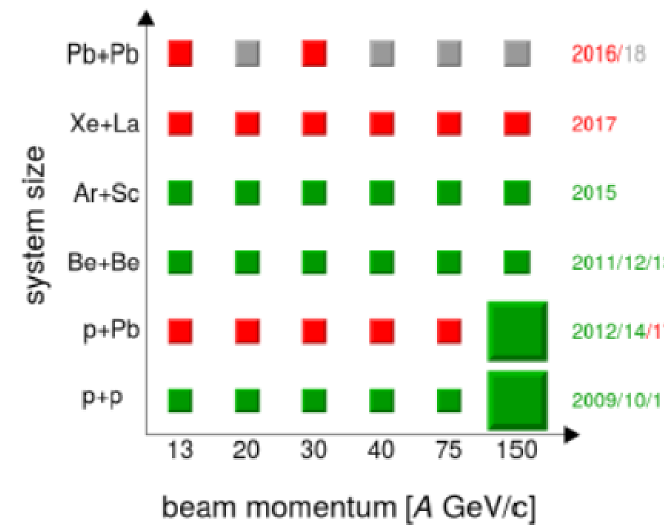


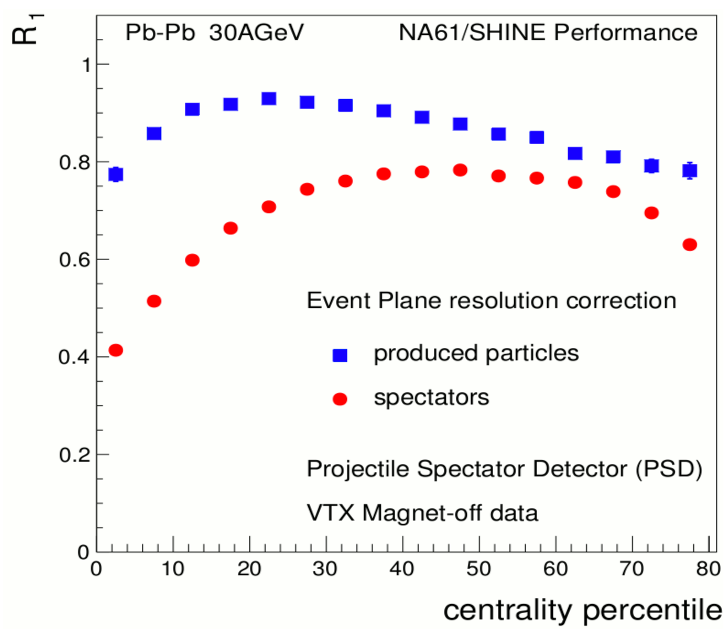


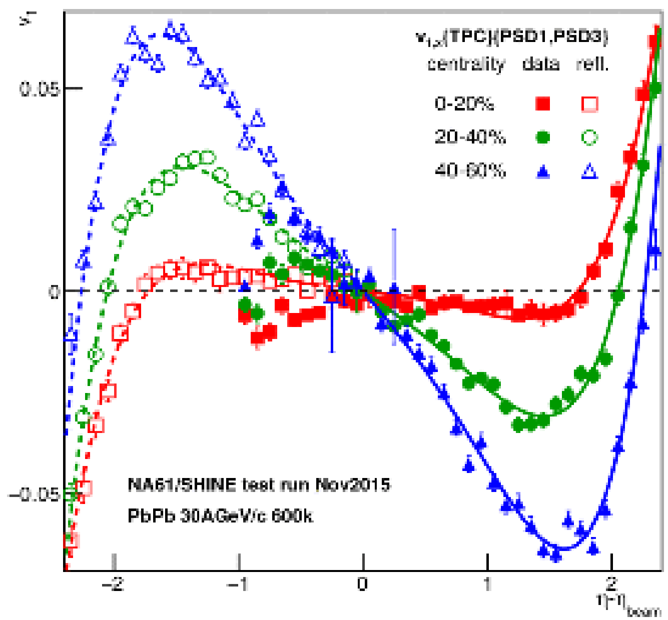
Prospects for directed flow measurements: NA61/SHINE

*Phys Rev C **68**, 034903 (2003) (NA49 Coll)*





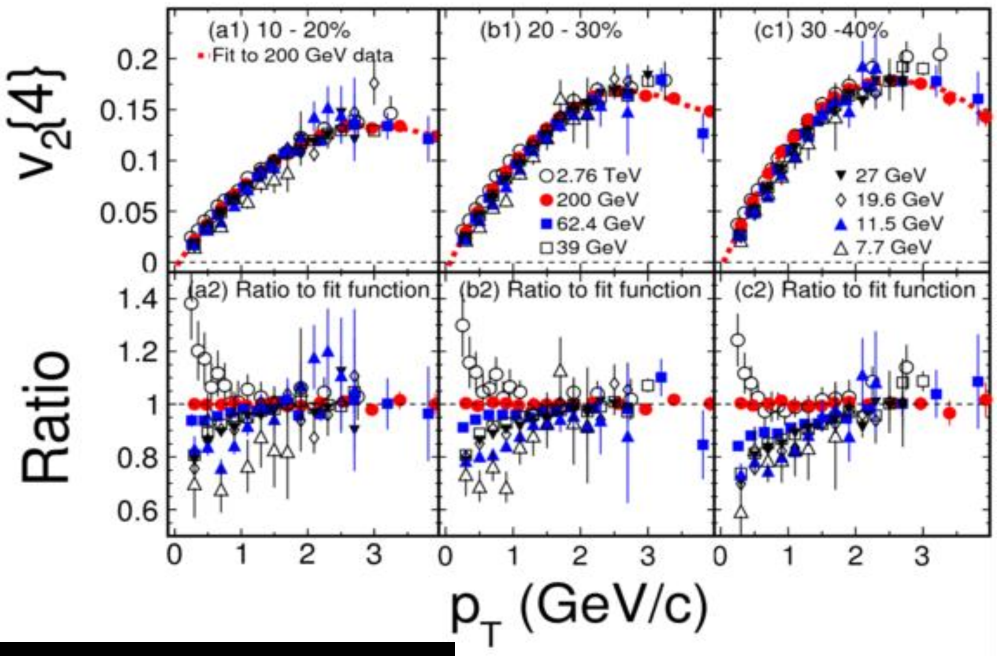




Addendum to the NA61/SHINE program http://cds.cern.ch/record/2059811

Beam Energy Dependence of Elliptic Flow (v_2)

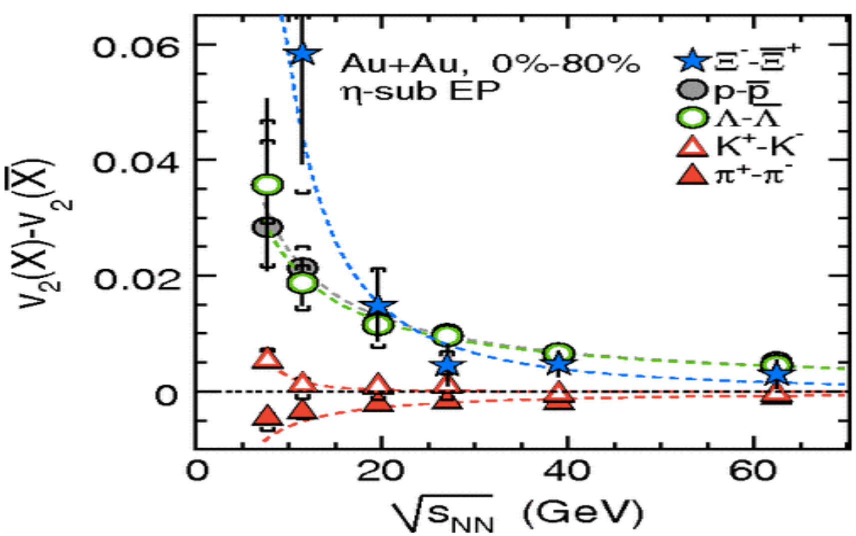
STAR: Phys. Rev. C 86 (2012) 54908



Surprisingly consistent as the energy changes by a factor ~400
Initial energy density changes by nearly a factor of 10
No evidence from v2 of charged hadrons for a turn off of the QGP

How sensitive is v_2 to QGP?

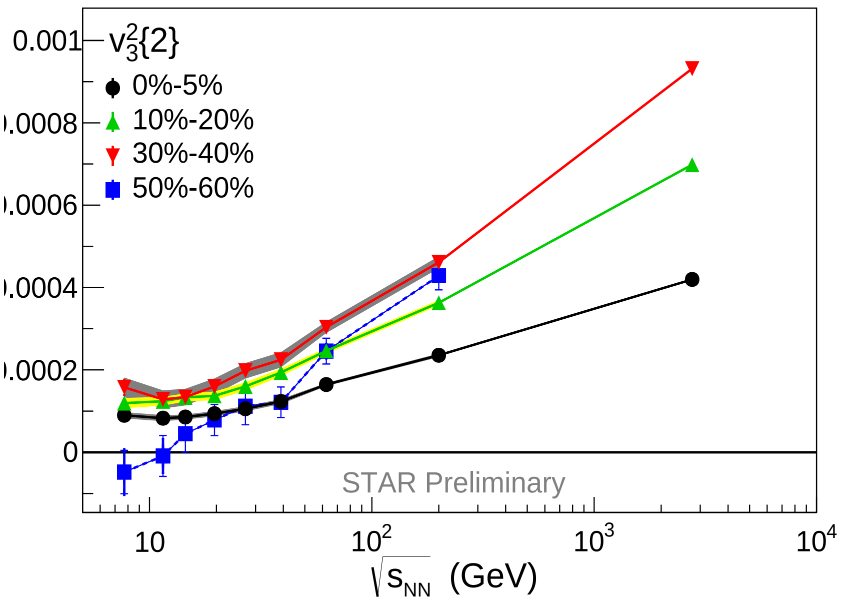
Phys. Rev. Lett. 110, 142301 (2013)

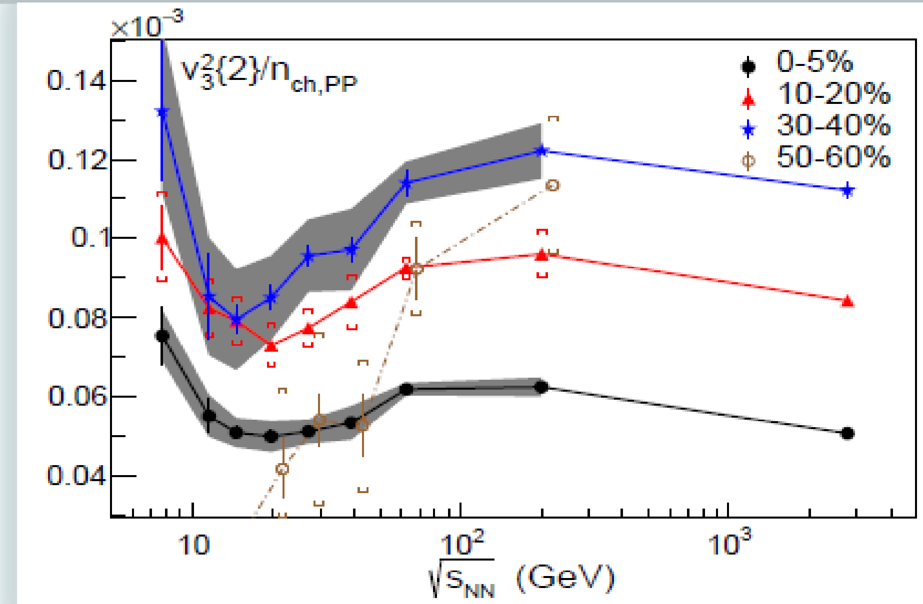


Substantial particle-antiparticle split at lower energies

- The number of quark scaling in elliptic flow is broken at low energies
- Do ϕ-mesons or multi-strange particles deviate?

Beam Energy Dependence of Triangle Flow (v_3)



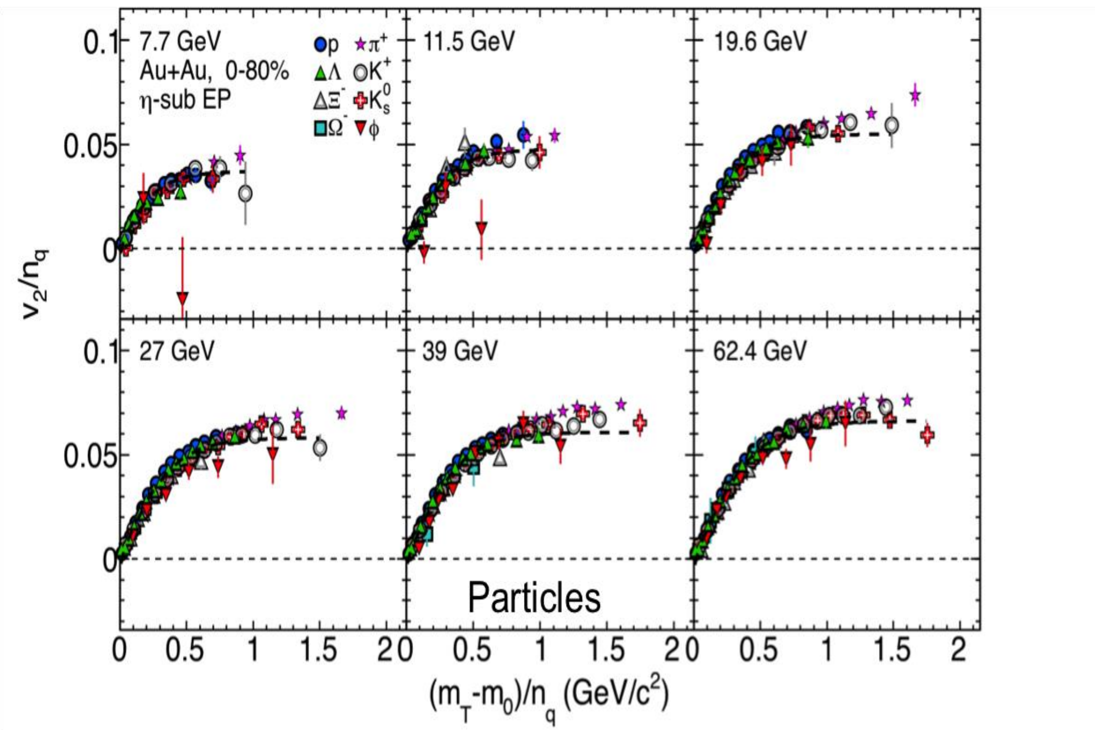


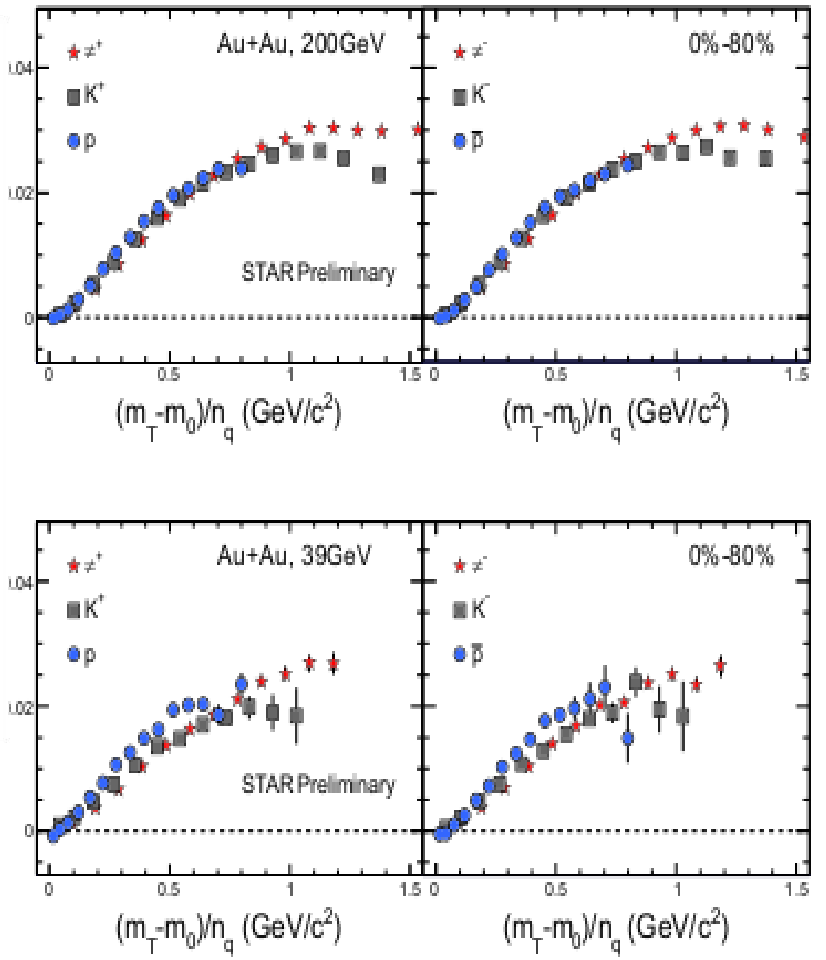
Models show that higher harmonic coefficients are more sensitive to the existence of a QGP phase. In models, v_3 goes away when the QGP phase disappears *J. Auvinen, H. Petersen, Phys. Rev. C 88, 64908, B. Schenke et.al., Phys. Rev. C 85, 024901*

STAR results show that v_3 vanishes for peripheral collisions at lowest RHIC BES energy. Minimum are observed for centralities bins in 0-50% collisions for $v_3^2/n_{ch,pp.}$ (pseudorapidity density of charged-particle multiplicity per participating nucleon pair) (***PRL 116, 112302 (2016)***)

Prospects for (v_3) PID measurements: STAR BES 1-2

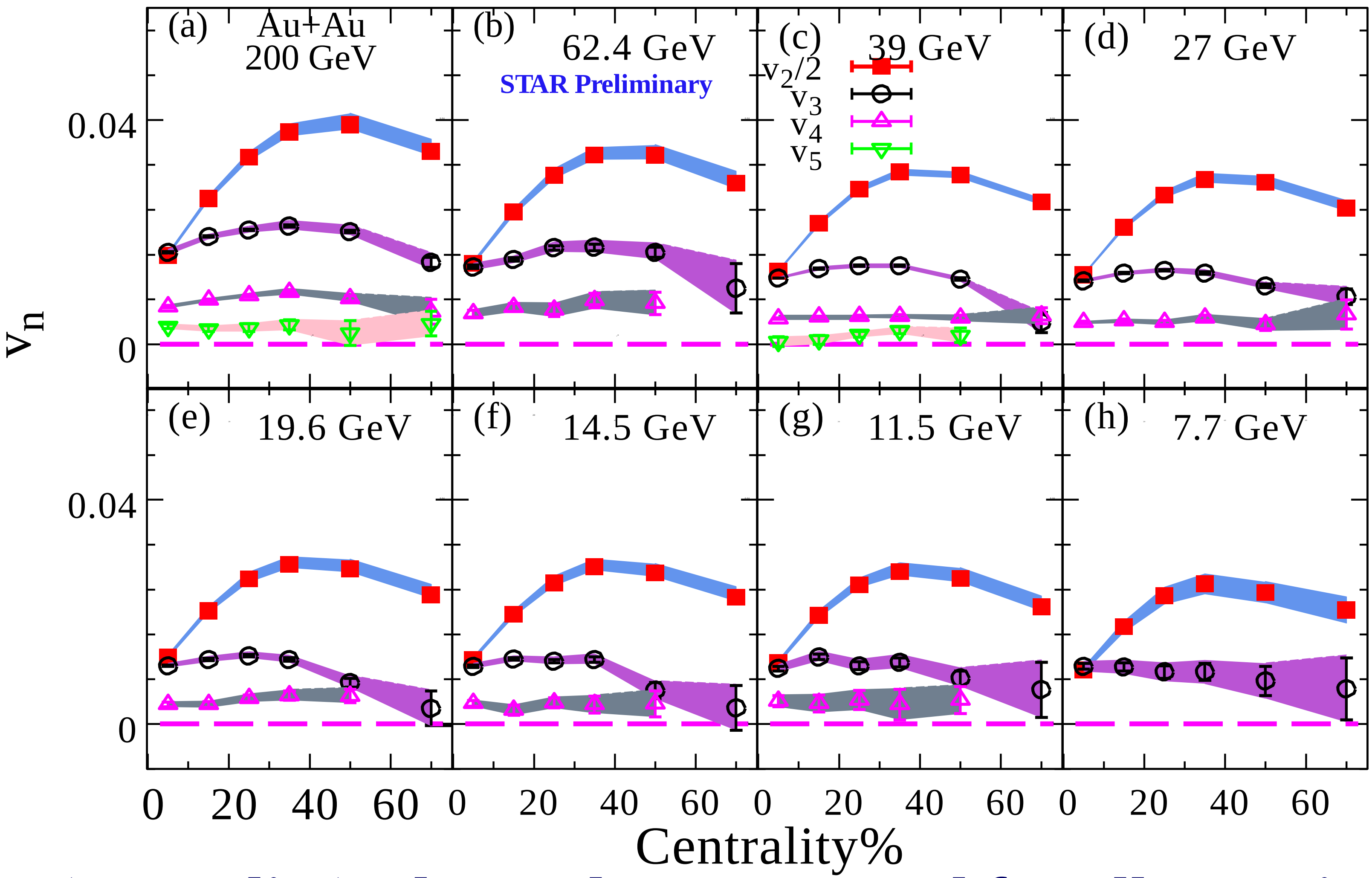
Phys. Rev. C 88, 014902 (2013)





- NCQ-scaling holds for v2 of particles and anti-particles separately at all energies
- Do ϕ-mesons or multi-strange particles deviate?
- NCQ-scaling is broken for v3 of particles and anti-particles separately for < 39 GeV

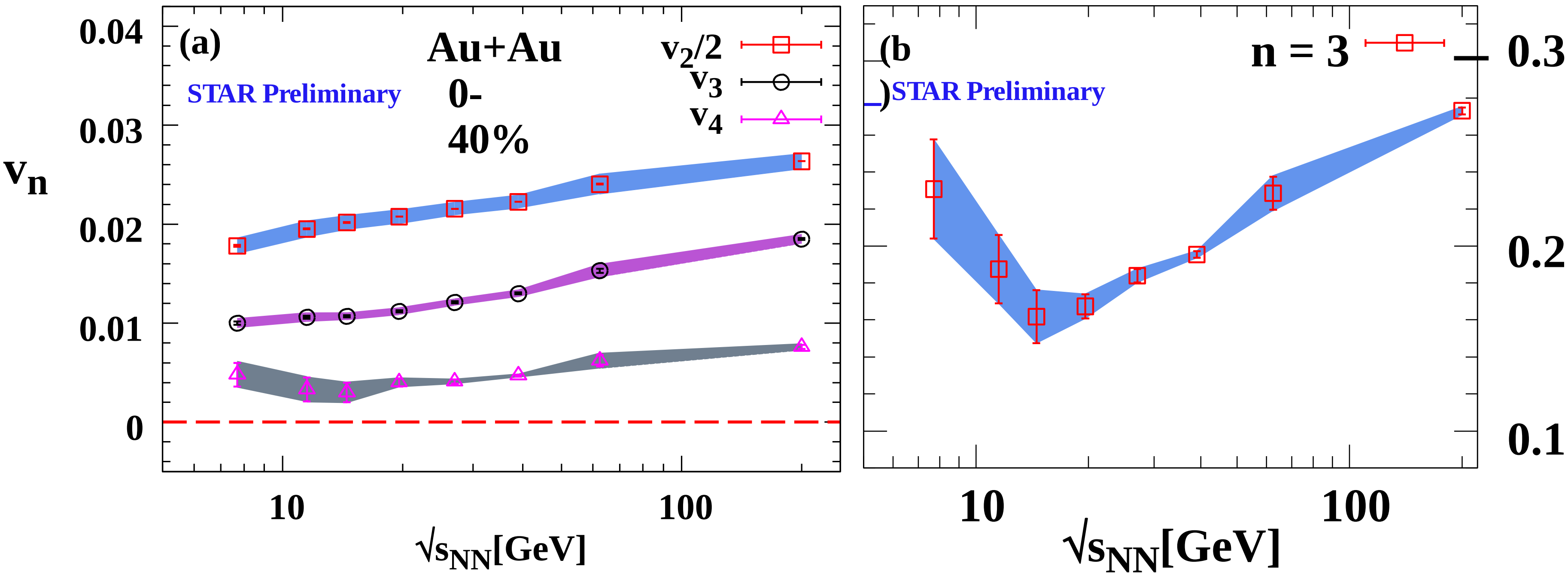
V_n (centrality) as a function of beam energy



V_n (centrality) shows the same trend for all energies from RHIC BES1: decreases with harmonic order n.

$$VC = \ln\left(\frac{(v_n)^{\frac{1}{n}}}{(v_2)^{\frac{1}{2}}}\right)\left(\frac{dN}{d\eta}\right)^{\frac{1}{3}}$$

$$VC \propto \frac{\eta}{s}$$



V_n shows a monotonic increase with beam energy. The viscous coefficient, which encodes the transport coefficient (*η/s*), indicates a non-monotonic behavior as a function of beam energy.

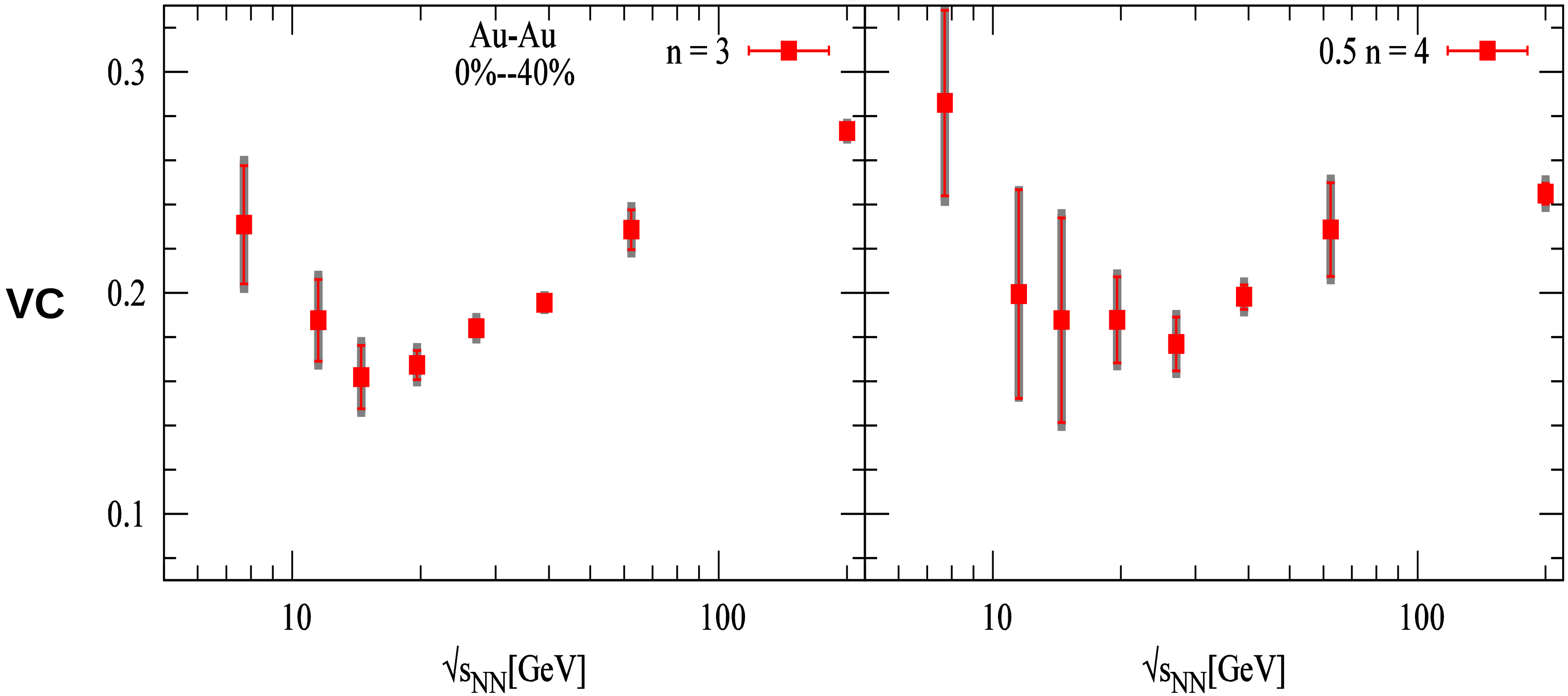
Viscous coefficient

$|\eta| < 1$ and $|\Delta\eta| > 0.7$

$0.2 < p_T < 4\mathrm{GeV}/c$

$$VC = \ln\left(\frac{(v_n)^{\frac{1}{n}}}{(v_2)^{\frac{1}{2}}}\right)\left(\frac{dN}{d\eta}\right)^{\frac{1}{3}}$$

$$VC \propto \frac{\eta}{s}$$

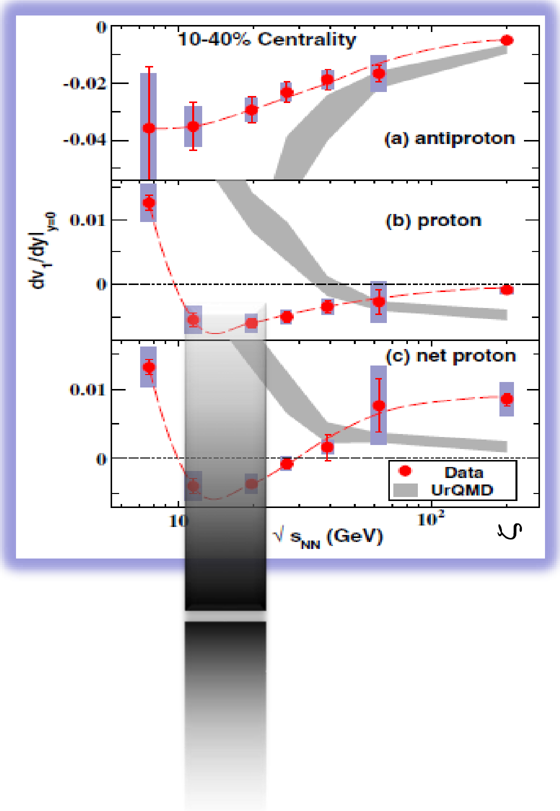


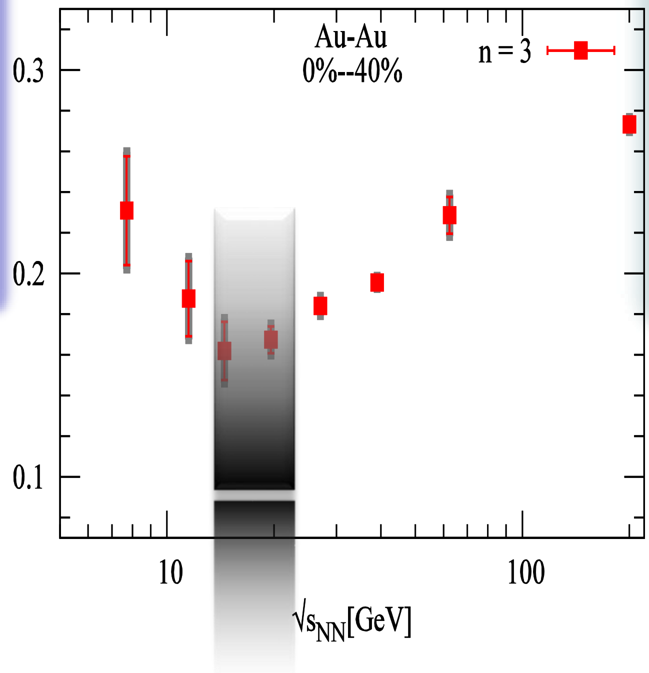
➢ **The viscous coefficient vc shows a non-monotonic behavior with beam energy in both cases, n = 3 and n = 4.**

STAR Collaboration, Niseem Magdy, SQM 2016

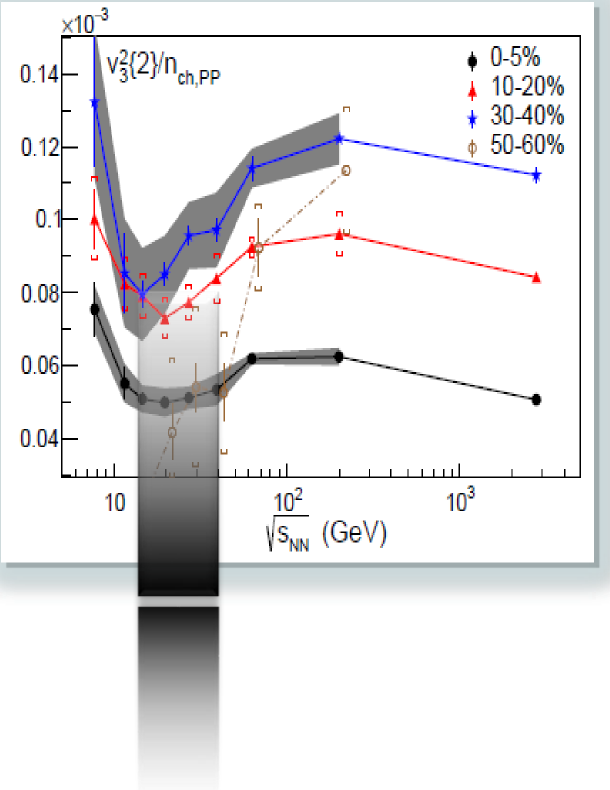
STAR data: Anomalies in the Pressure and η/s?

PRL 112,162301(2014)





PRL 116, 112302 (2016)



Region of interest $\sqrt{s_{NN}}\lesssim$20 GeV, however, is complicated by a changing B/M ratio, baryon transport dynamics, longer nuclear passing times, etc. ***Requires concerted modeling effort.***

Elliptic Flow at AGS, SIS: from in-plane to out-of-plane (1)

VOLUME 83, NUMBER 7 PHYSICAL REVIEW LETTERS 16 AUGUST 1999

Elliptic Flow: Transition from Out-of-Plane to In-Plane Emission in Au + Au Collisions

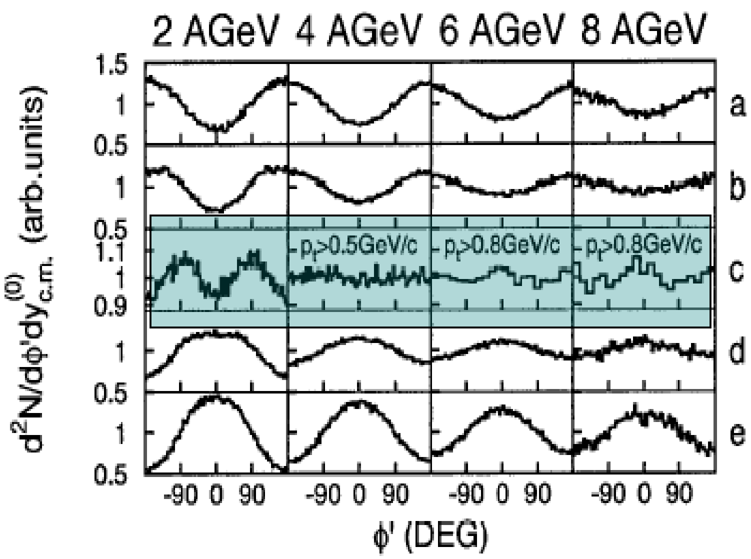
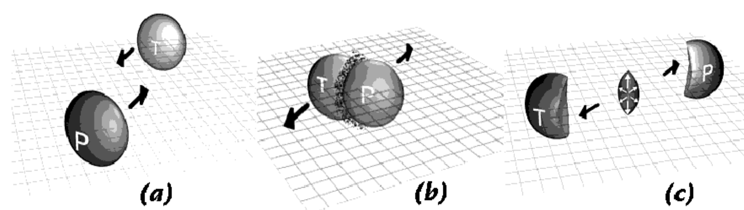


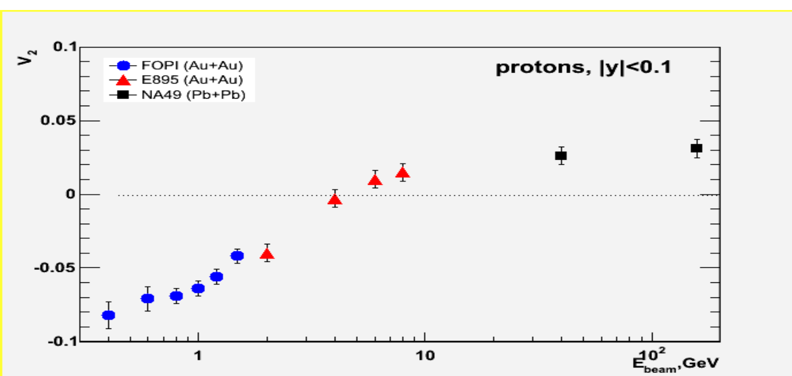
FIG. 2. Azimuthal distributions (with respect to the reconstructed reaction plane) for 2A, 4A, 6A, and 8A GeV Au + Au.

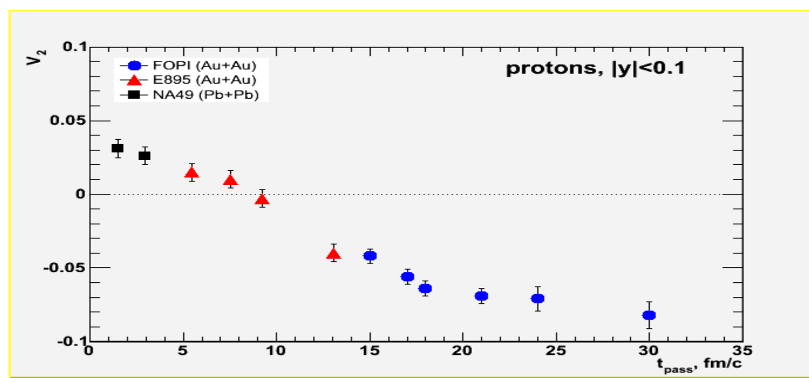
Passage time: $2R/(\beta_{cm}\gamma_{cm})$

Expansion time: R/c_s

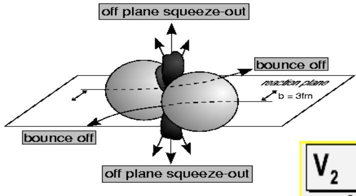
$c_s = c\sqrt{dp/d\varepsilon}$ **- speed of sound**







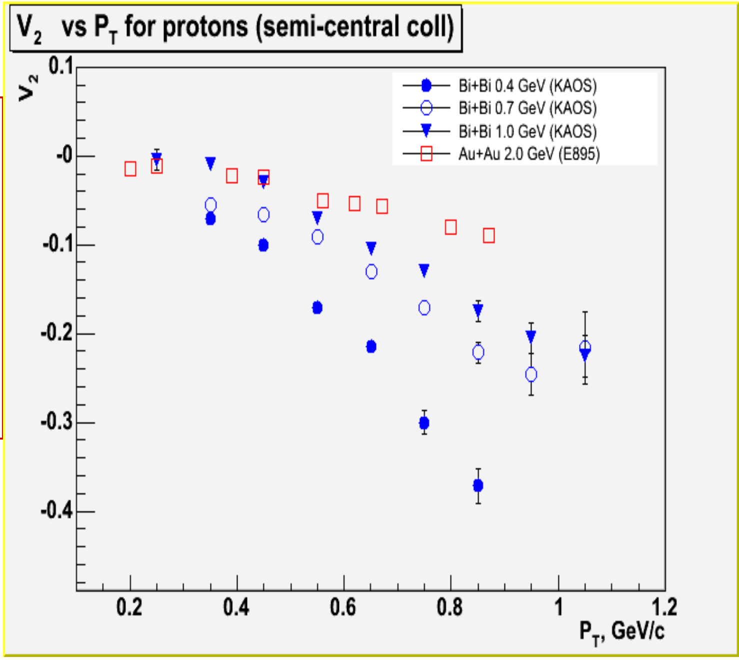
Squeeze-out Mechanism



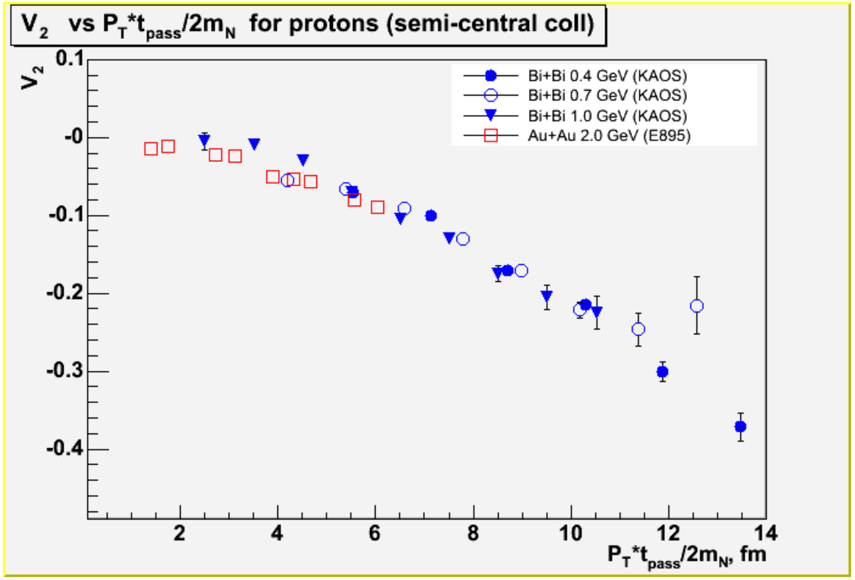
(KAOS – Z. Phys. A355 (1996); (E895) - PRL 83 (1999) 1295

Particle emitted in the center-of-mass of the system and moving in a transverse direction with velocity v_T **will be shadowed by spectators during the passage time:** $t_{pass}=2R/(\beta_{cm}\gamma_{cm})$ simple geometry estimate $\longrightarrow$ $v_T t_{pass}/2 > R-b/2$ **or**

$$v_T > (1-b/2R)(\beta_{cm}\gamma_{cm})$$



V2 will increase with v_T and impact parameter b

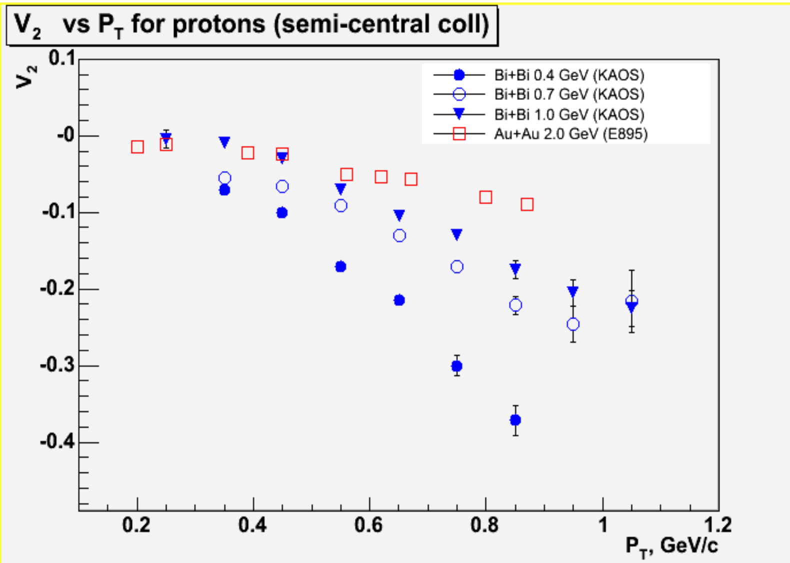


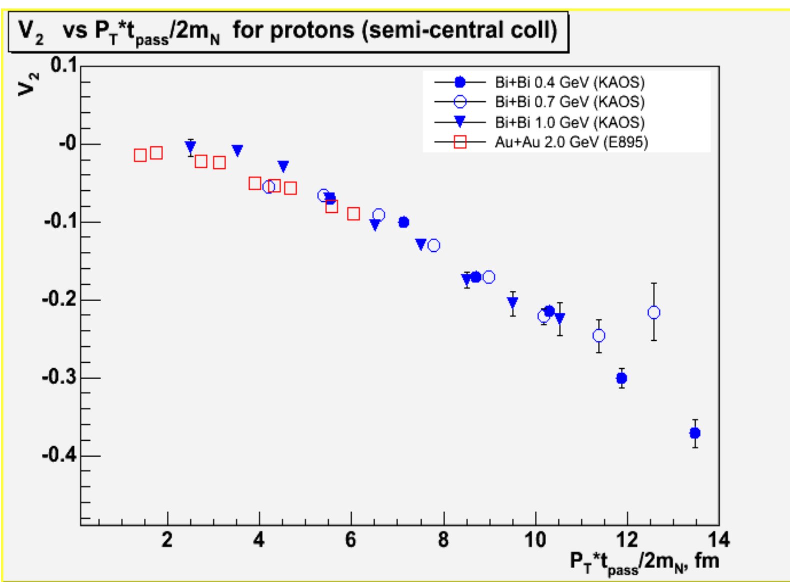
Squeeze-out contribution reflects the ratio : $c_s/(\beta_{cm}\gamma_{cm})$

$c_s=c\sqrt{dp/d\varepsilon}$ - speed of sound and does not change significantly over this beam energy range

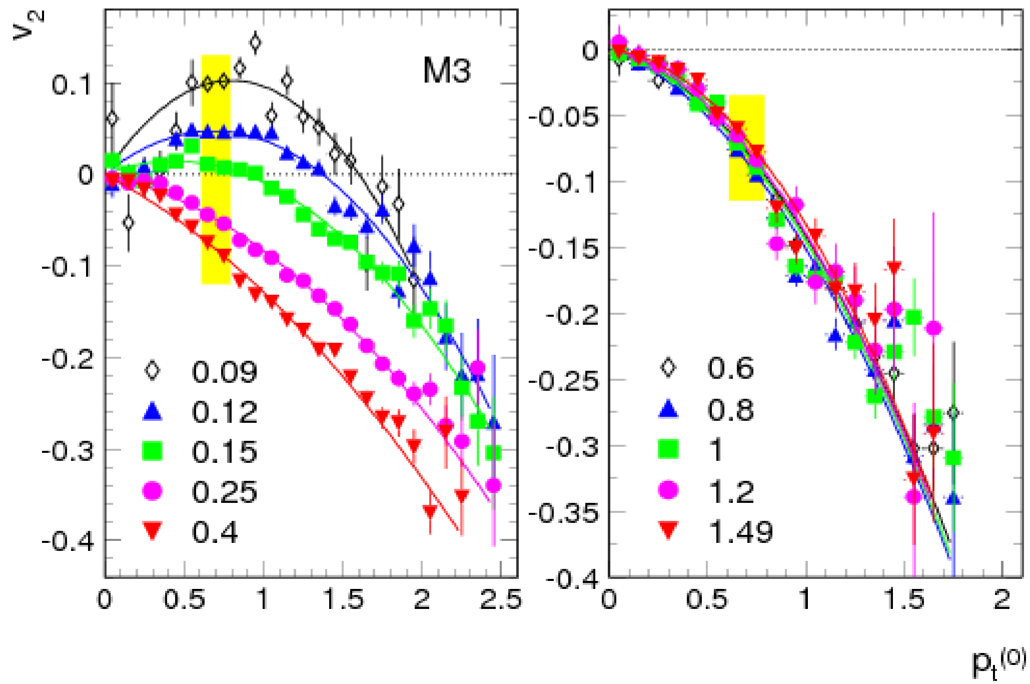
v_2 Flow at SIS-AGS: scaling relations

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





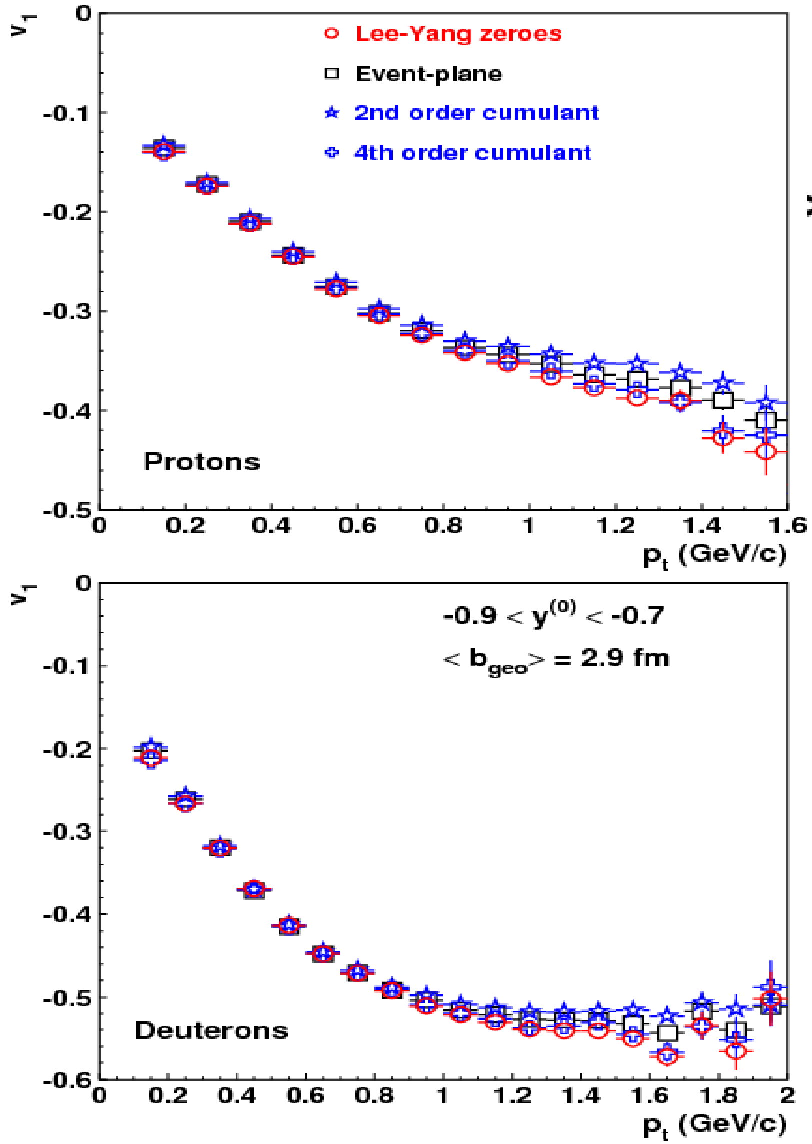
FOPI: v_2 of protons from
Elab=0.09 to 1.49 GeV
Phys.Lett. B612 (2005) 173-180



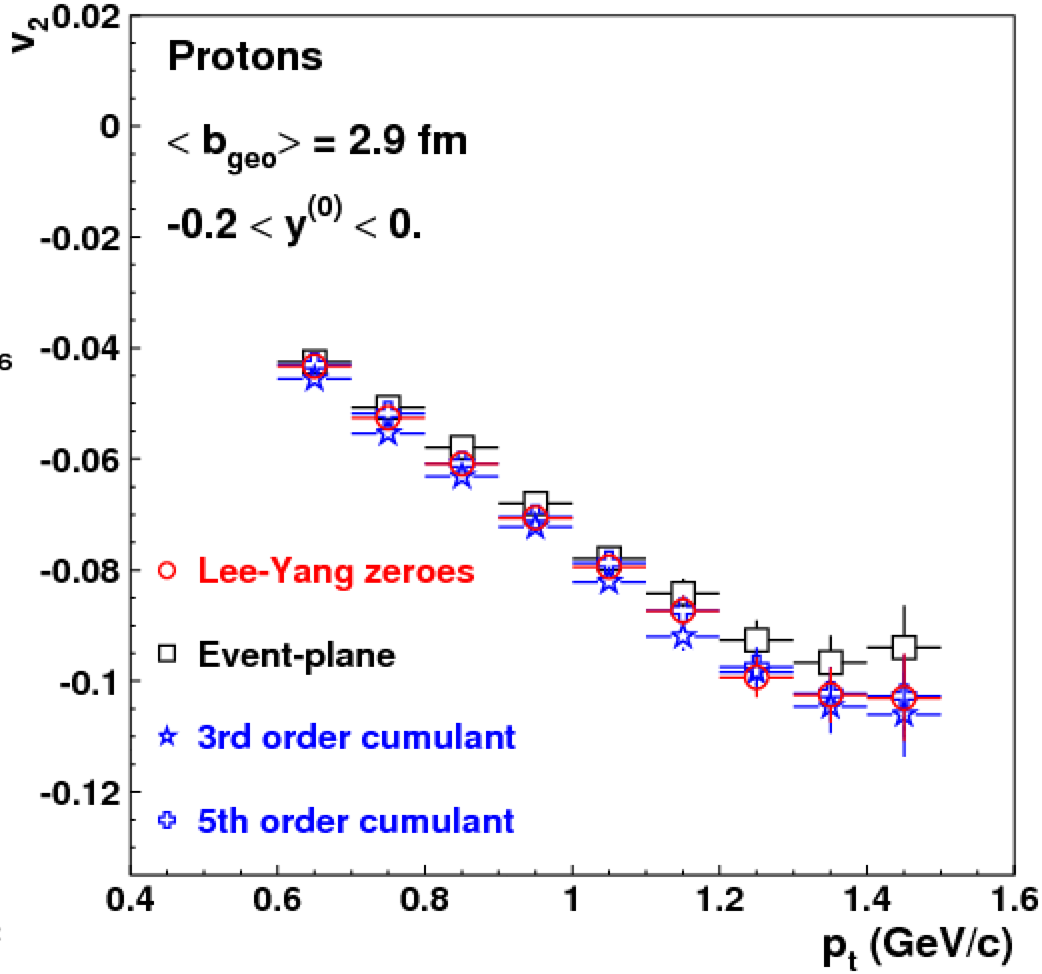
Pt dependence of v2 of protons revealing a rapid change with incident energy below 0.4 AGeV, followed by an almost perfect scaling at the higher energies: 0.4 -2AGeV

.

Flow at SIS: non-flow / fluctuations



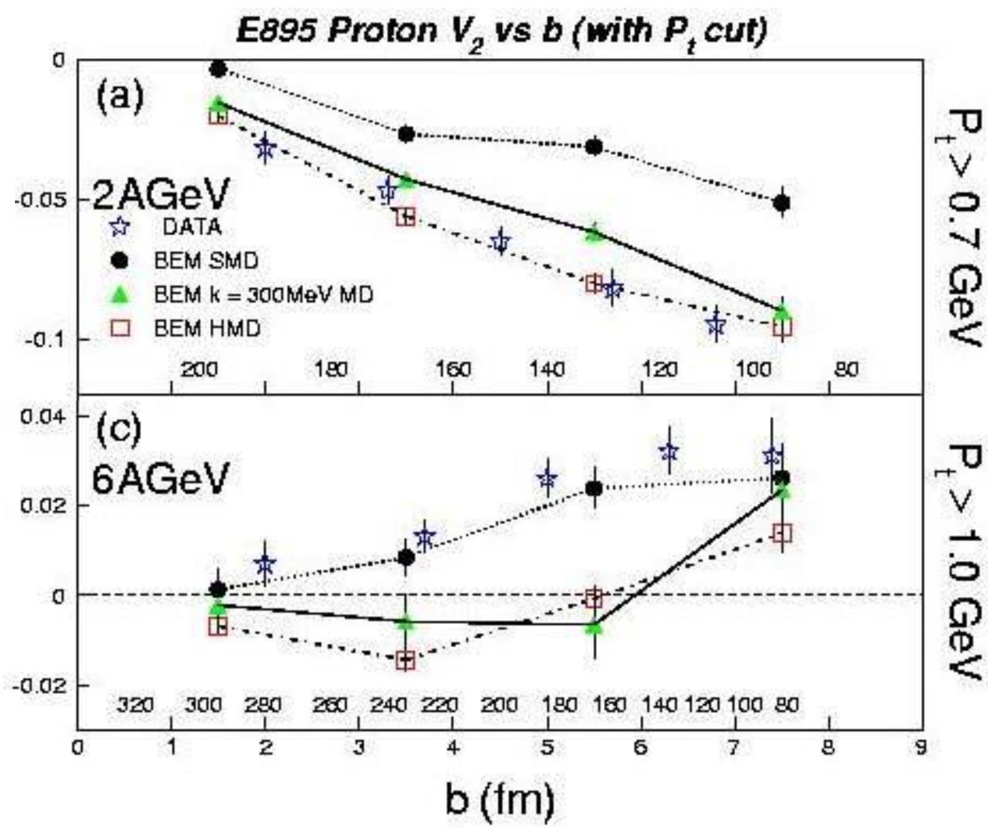
FOPI: Au+Au at 1AGeV
Phys. Rev. C 72 (2005) 011901

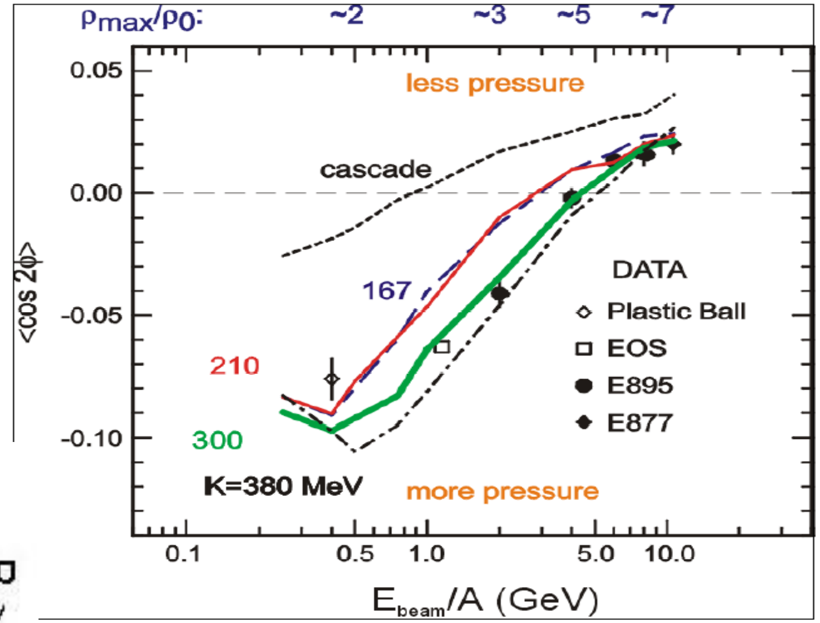


Elliptic Flow at AGS, SIS: from in-plane to out-of-plane (2)

Good Constraints for the Hadronic EOS

Differential Elliptic Flow in 2 - 6 A GeV Au + Au Collisions: Tighter Constraint for the Nuclear EOS
Phys. Rev. C **66**, 021901 (2002).

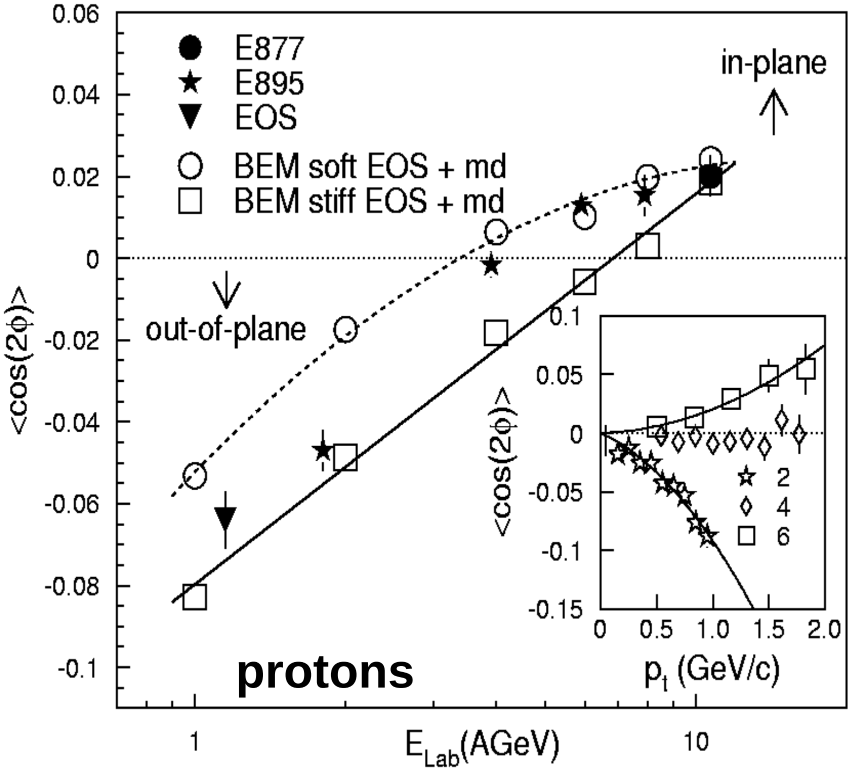




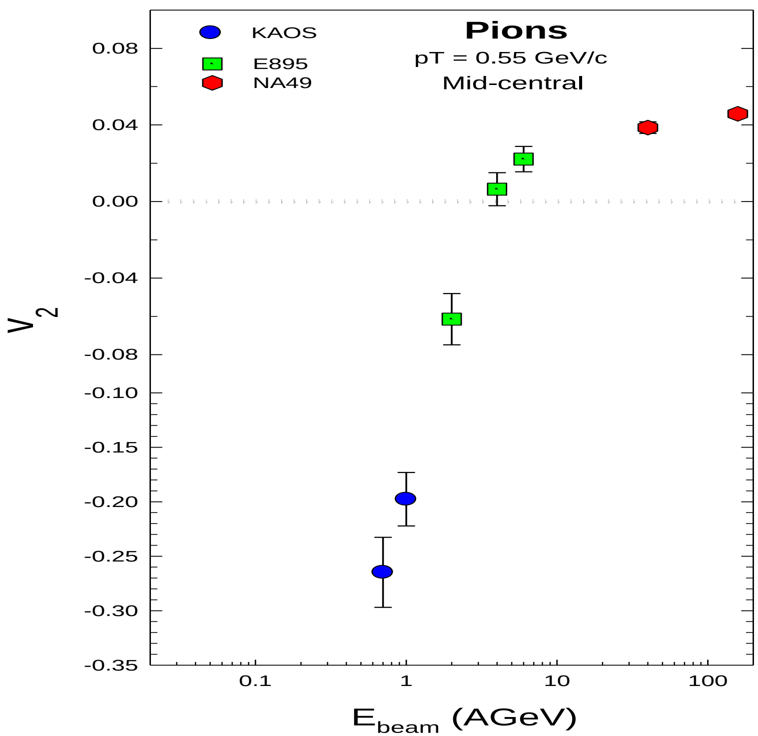
P. Danielewicz, R. Lacey, W.G. Lynch, Science 298 (2002) 1592

v_n Flow at AGS, SIS: from in-plane to out-of-plane (3)

Phys. Rev. Lett. **83**, 1295 (1999). E895



E895 preliminary ; SQM2004

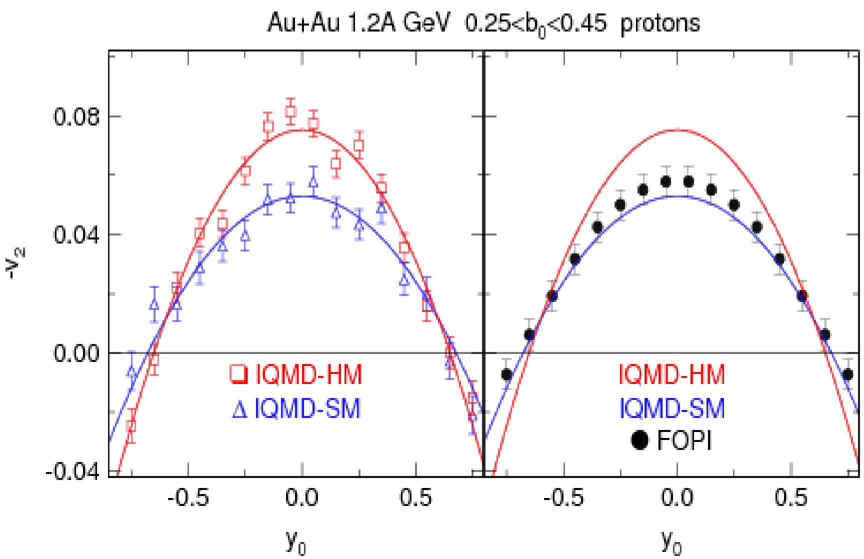


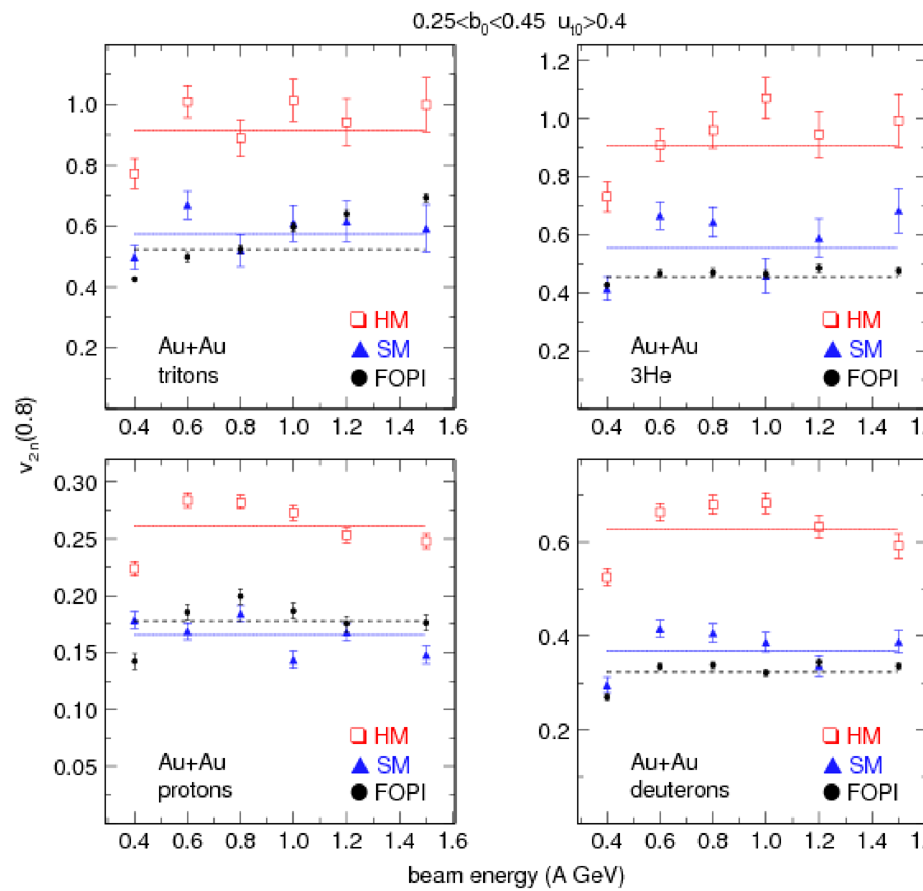
E895: for protons V2 changes sign at Elab=4 GeV. What about the other particle species? Other harmonics? Questions for STAR BES2, BM@N, CBM, NICA

Flow at SIS: rapidity dependence of v2 and EOS

HM – stiff momentum dependent with K=376 MeV
SM – soft momentum dependent with K=200 MeV

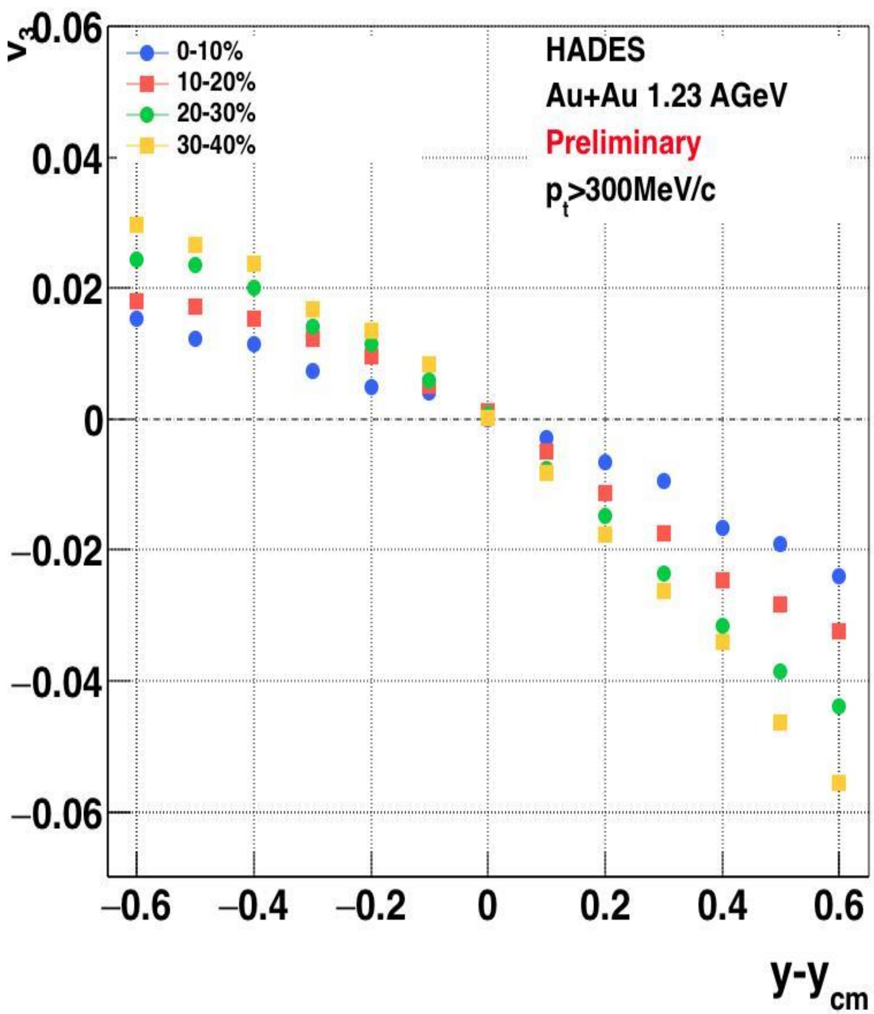
FOPI data : Nucl. Phys. A 876 (2012) 1
IQMD : Nucl Phys. A 945 (2016)



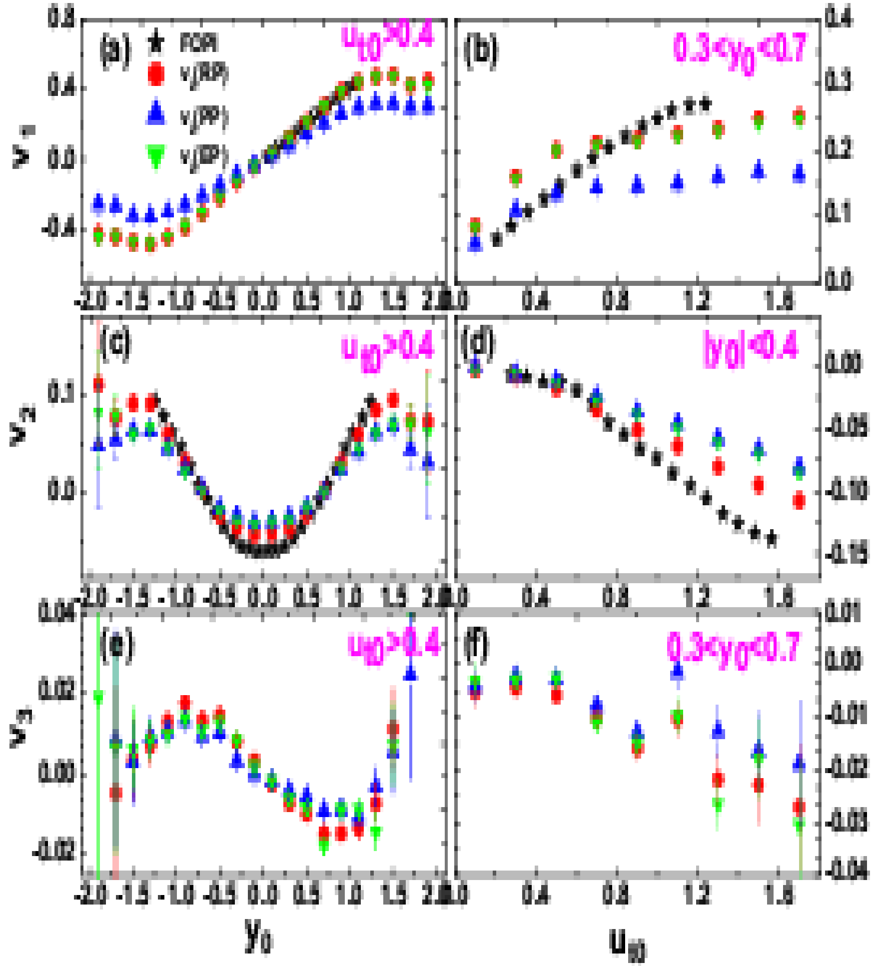


V2n=|V20|+|V22|
Fit: V2(y0)=V20+V22*Y0^2

Flow at SIS: Vn harmonics n>2

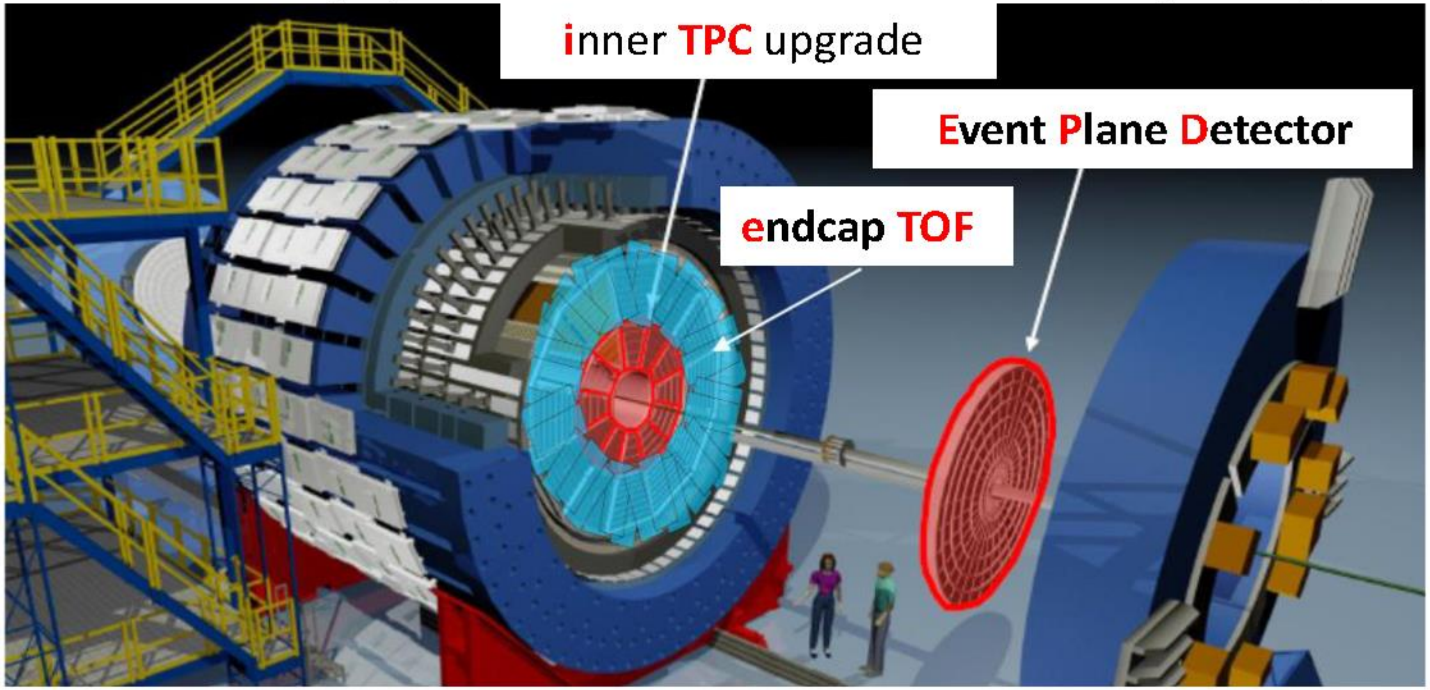


HADES preliminary QM2017



IQMD: Phys.Rev.C. 90(2014)

The STAR Upgrades and the FXT program



iTPC Upgrade:
- Improves tracking and acceptance
- Ready in 2019

EndCap TOF Upgrade:
- Improves PID and acceptance
- Ready in 2019

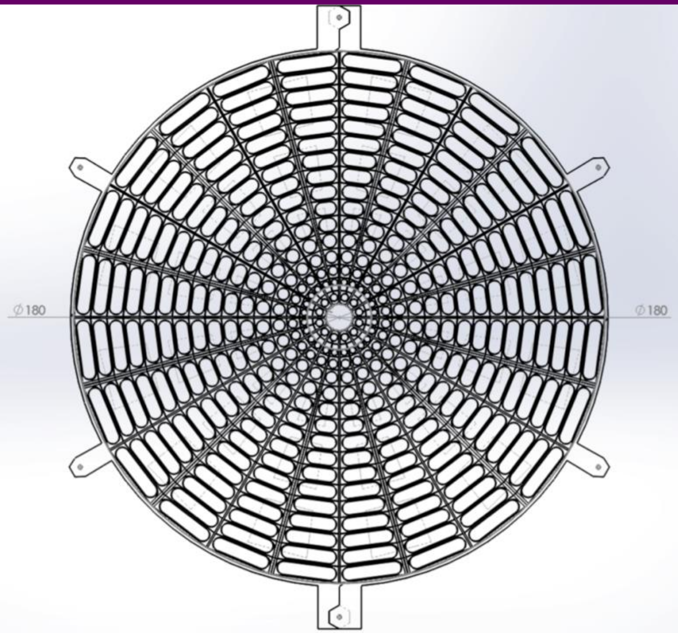
EPD Upgrade:
- Improves event plane resolution and centrality definition
- Ready in 2018

Star Note 0644 : Technical Design Report for the iTPC Upgrade

https://arxiv.org/pdf/1609.05102.pdf

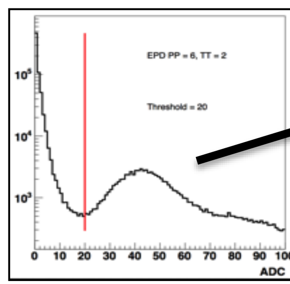
Star Note 0666 : An Event Plane Detector for STAR

STAR Event Plane Detector

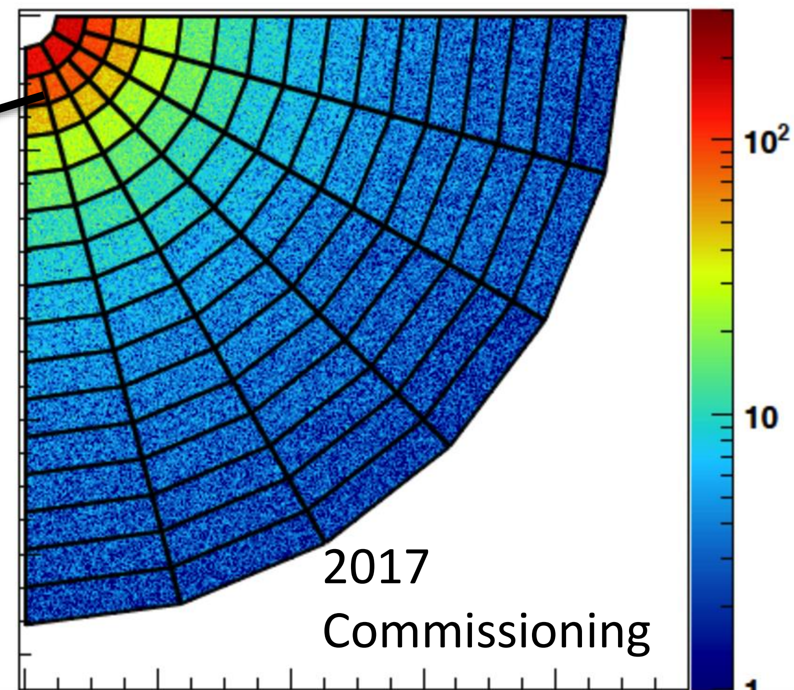


- 2 Wheels of 12 supersectors with 31 optically-isolated tiles
  - 1.2-cm-thick scintillator
  - 3 turns of Wavelength shifting (WLS) fiber
- Total of 12x31x2=**744 channels**

- Successful install of 1/8th in 2017
- Construction complete
  - Install in Jan 2018
- EP resolution improved by ~1.5
- Time Resolution ~1 ns



All 93 channels show good signals ✓



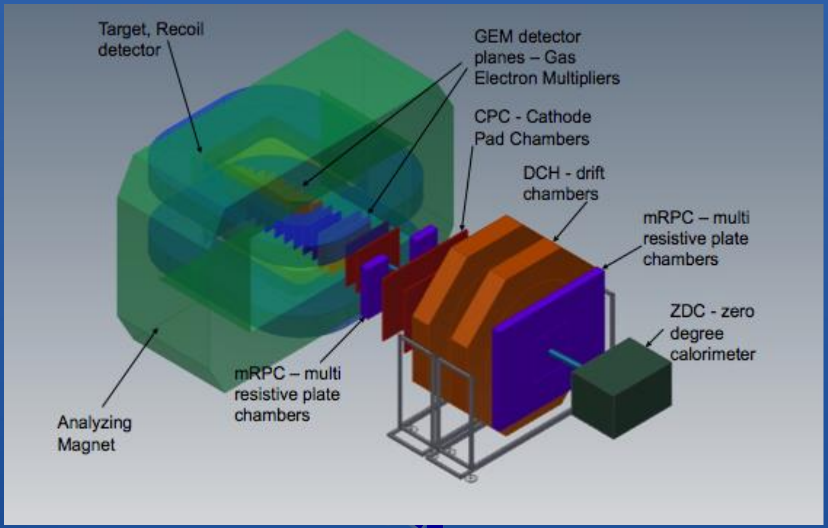
FXT in BES-II: Run 19

Beam Energy (GeV/nucleon)	$\sqrt{s_{NN}}$ (GeV)	Run Time	Species	Number Events
5.75	3.5	2 days	Au+Au	100M MB
7.3	3.9	2 days	Au+Au	100M MB
9.8	4.5	2 days	Au+Au	100M MB
13.5	5.2	2 days	Au+Au	100M MB
19.5	6.2	2 days	Au+Au	100M MB
31.2	7.7	2 days	Au+Au	100M MB

- iTPC and eTOF upgrades will be available
- Would need 100 Million Events at each energy to make the sensitivity of BES-II, 2 days per energy (3.5 GeV – 7.7 GeV)
- Data rate is DAQ limited
- Data at 7.7 GeV would provide an overlap energy with the collider mode

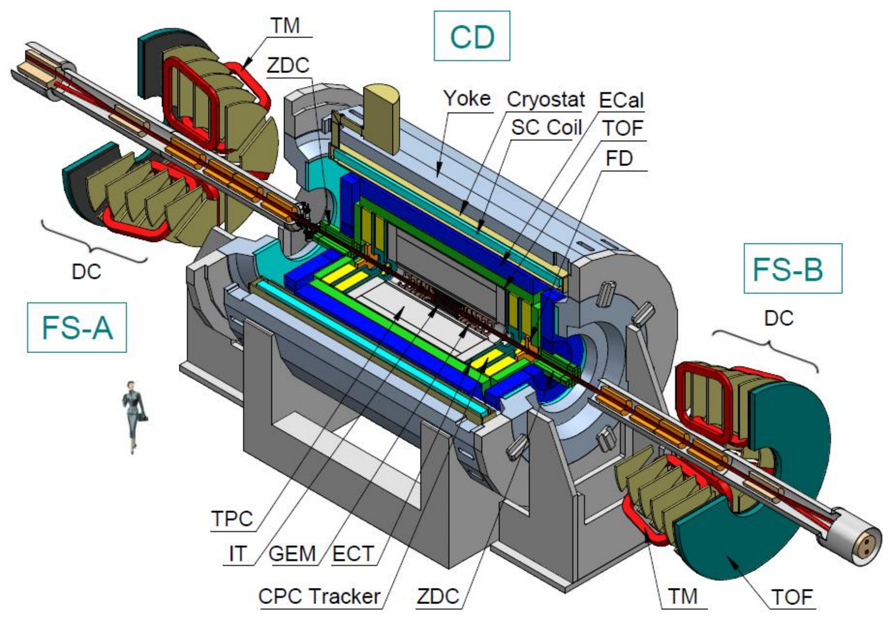
NICA detectors

Baryonic Matter at Nuclotron (BM@N)



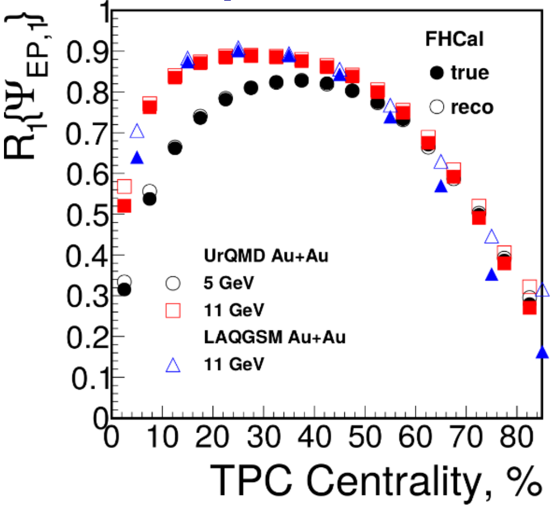
Almost all detector subsystems passed Technical Project stage and ready to the mass production

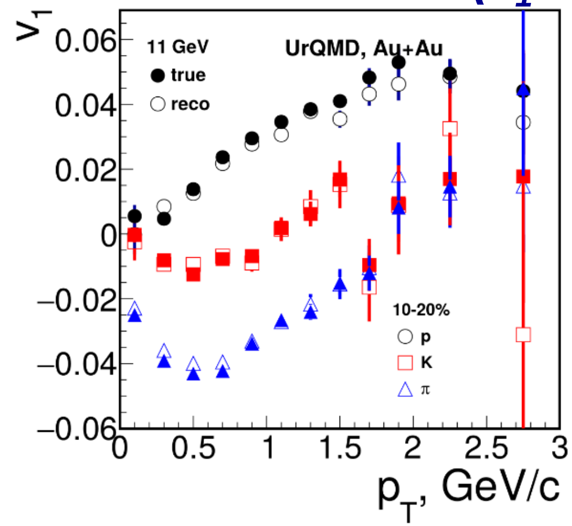
MultiPurpose Detector (MPD)

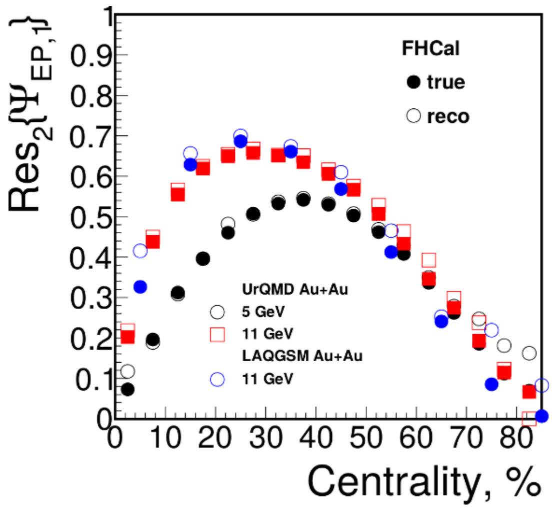


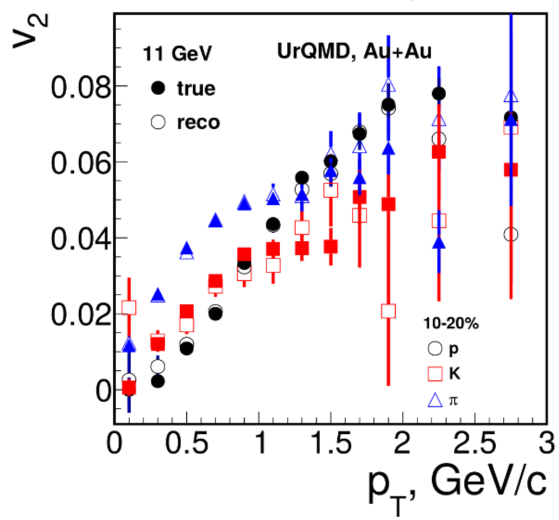
Flow performance: v_n of charged hadrons: MPD (NICA)

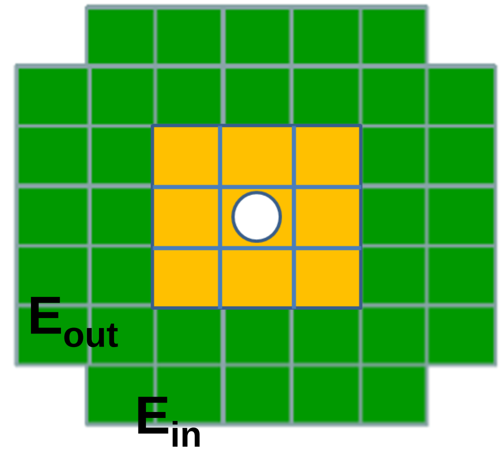
event plane resolution ***flow harmonics (v_1/v_2)***





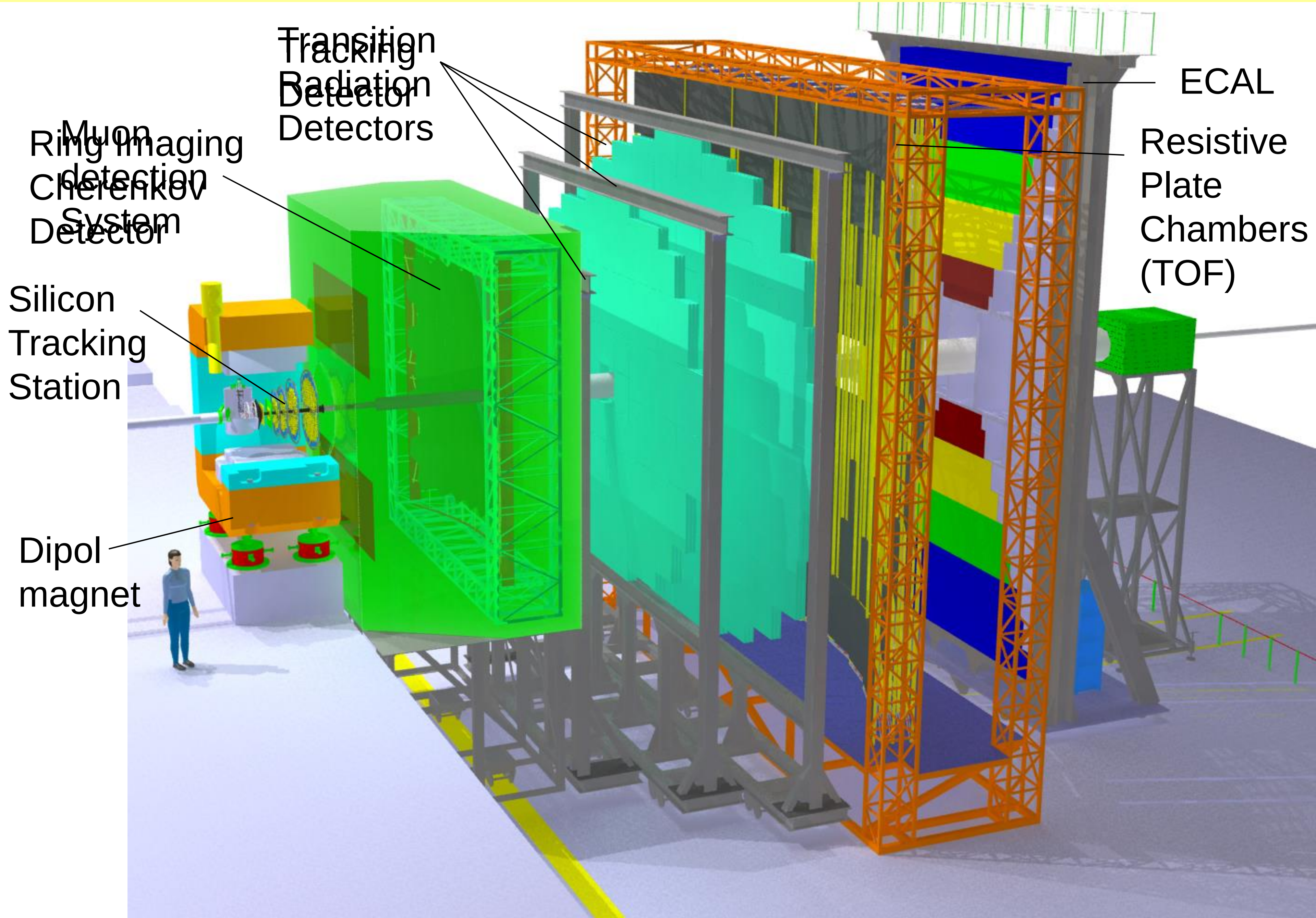




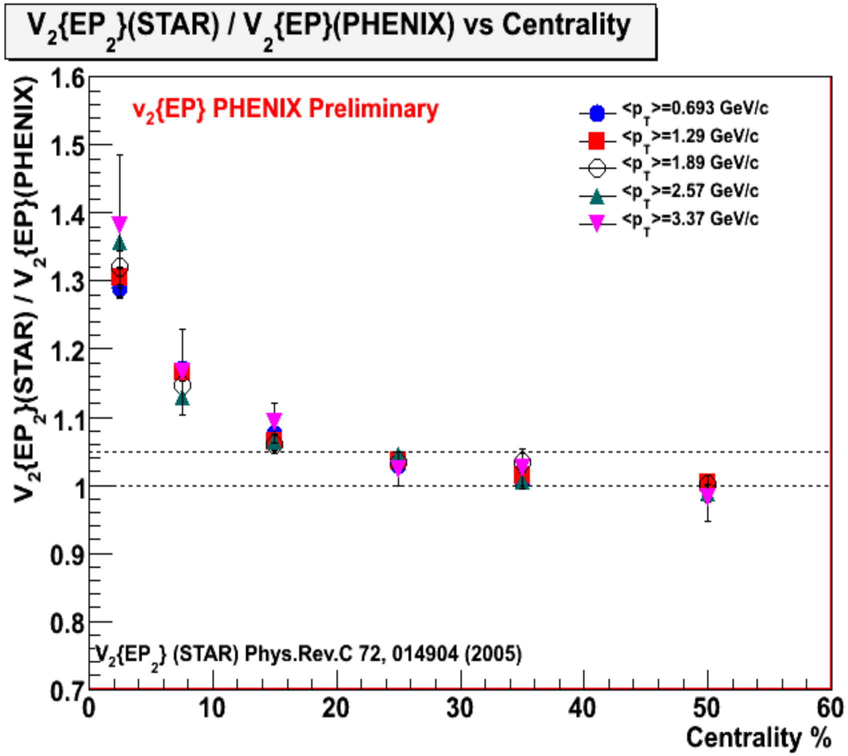


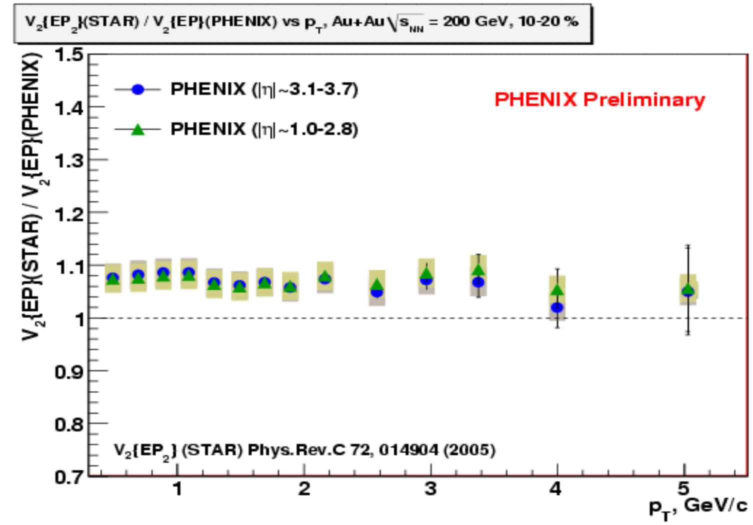
FHCal coverage:
2.2<|η|< 4.8

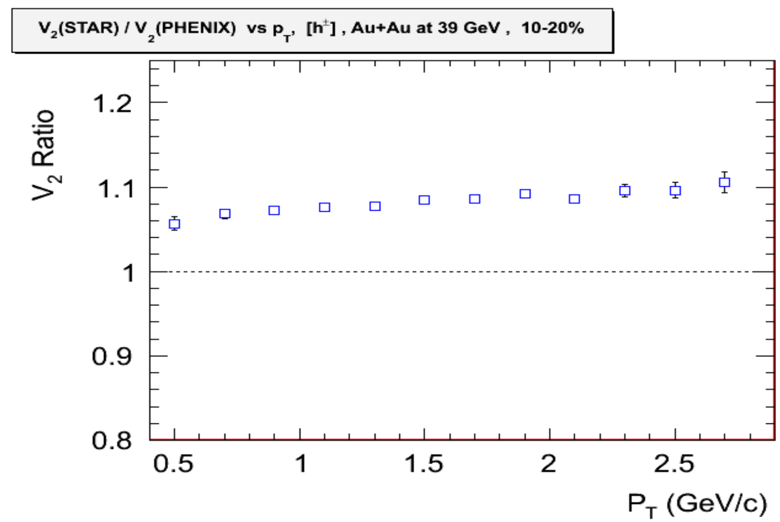
The Compressed Baryonic Matter Experiment

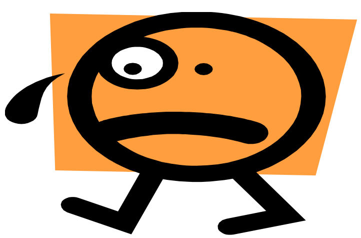


Comparison of PHENIX vs STAR: v2 at 39-200 GeV





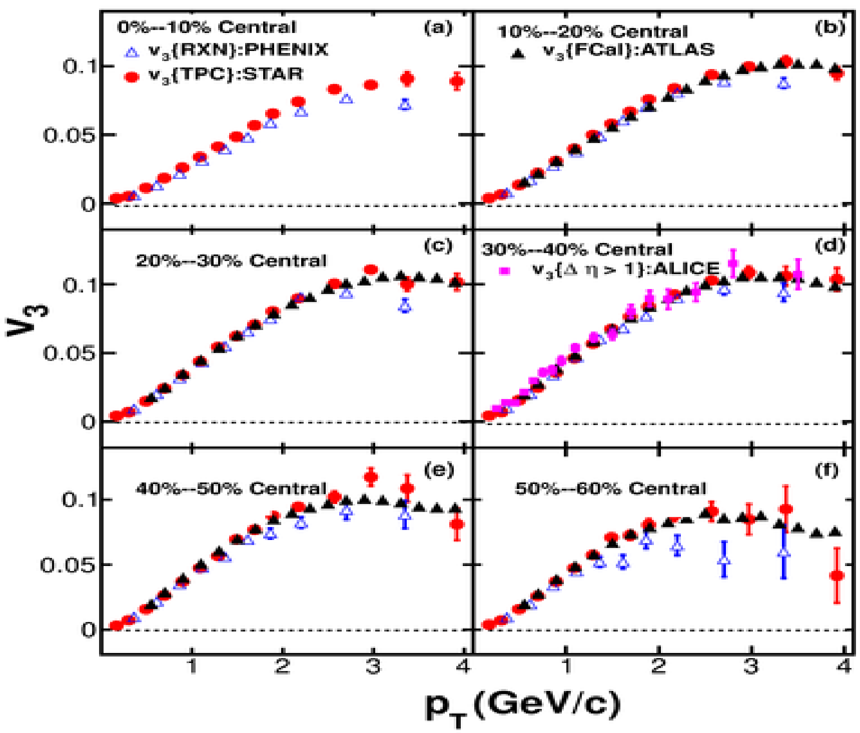


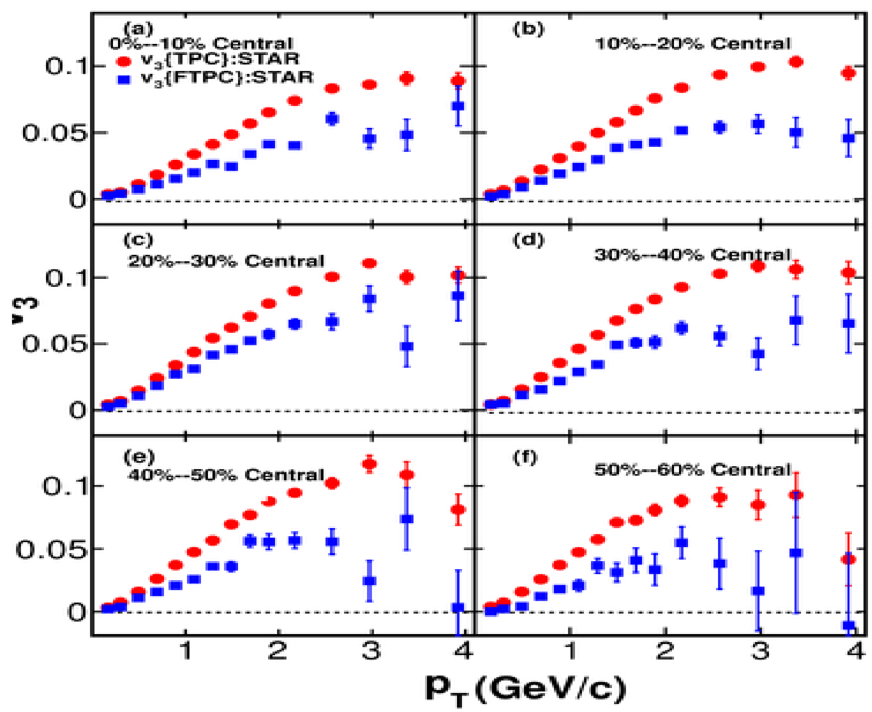


For 0-20% central collisions STAR V_2 > PHENIX V_2 : do we have the same centrality definition between experiments?

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

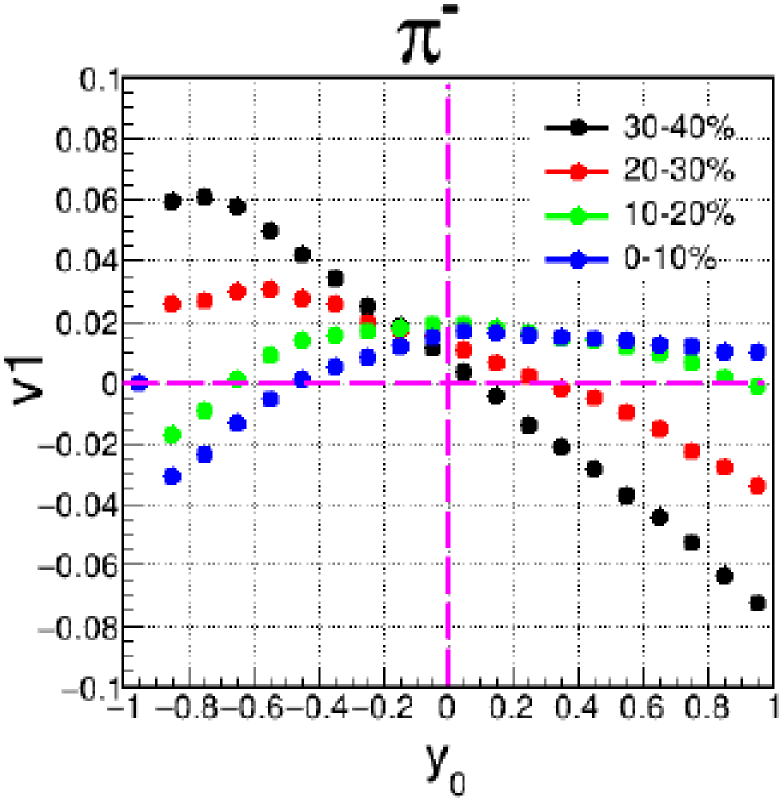
STAR: Third Harmonic Flow of Charged Particles in Au+Au Collisions at 200 GeV
Phys. Rev. C **88** (2013) 14904

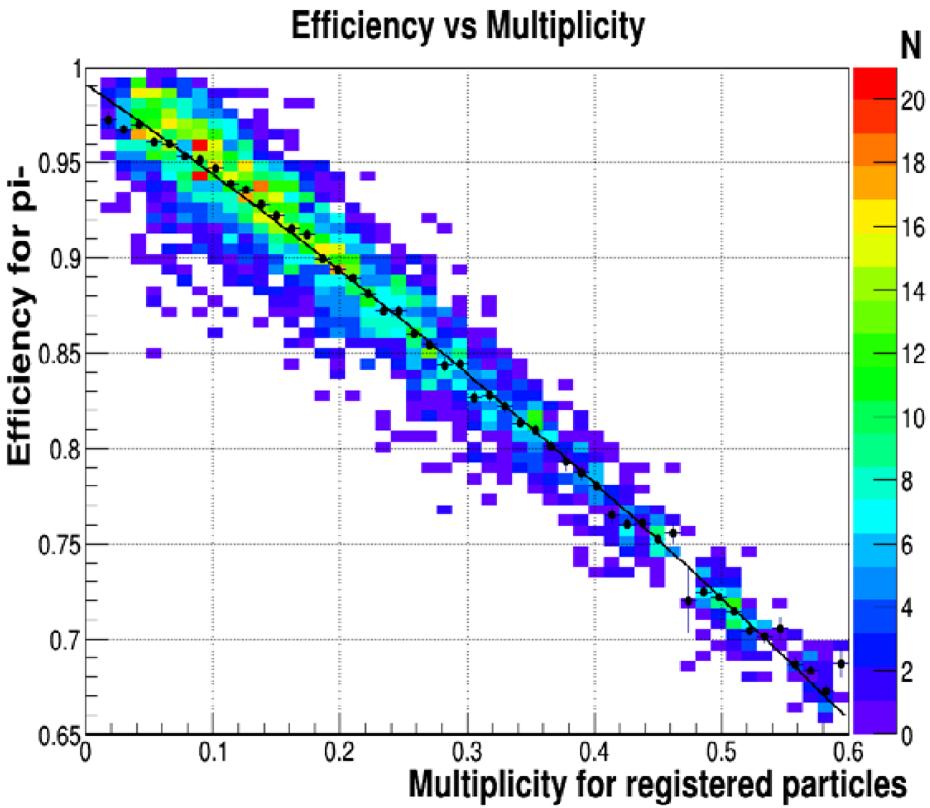


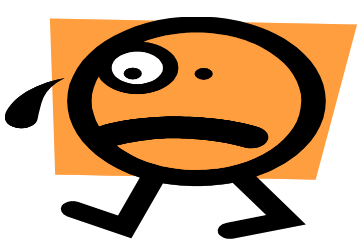


Do we understand the difference in v3 measurements between STAR and PHENIX ?

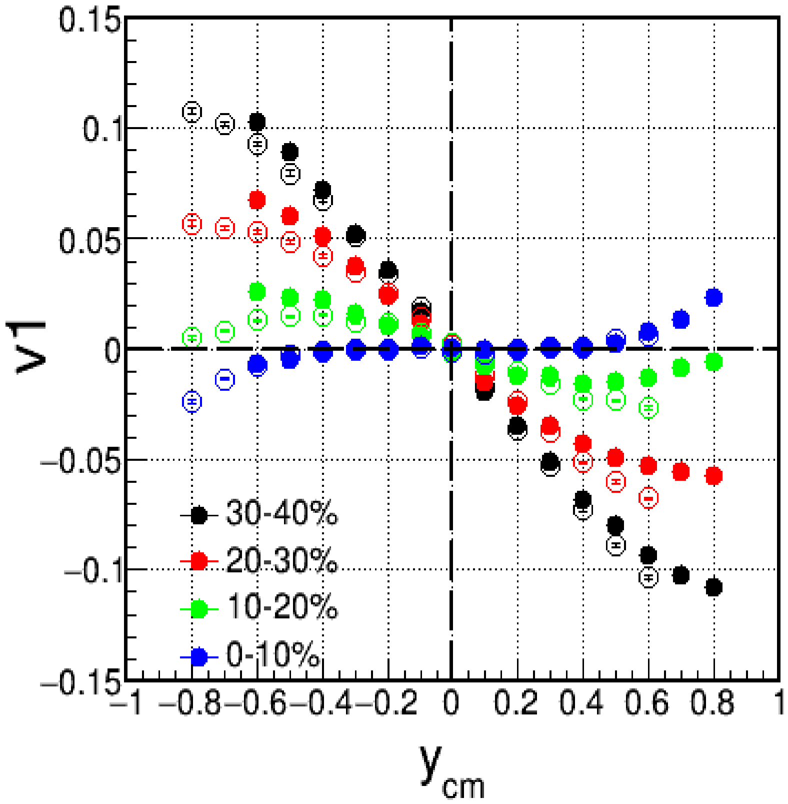
Directed flow of pions in HADES

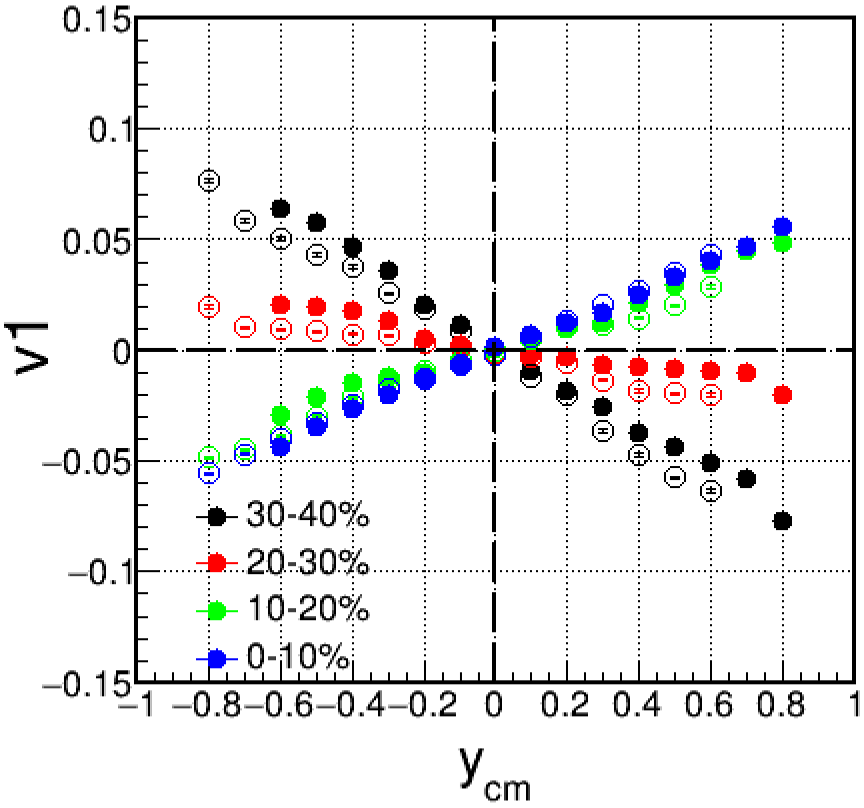




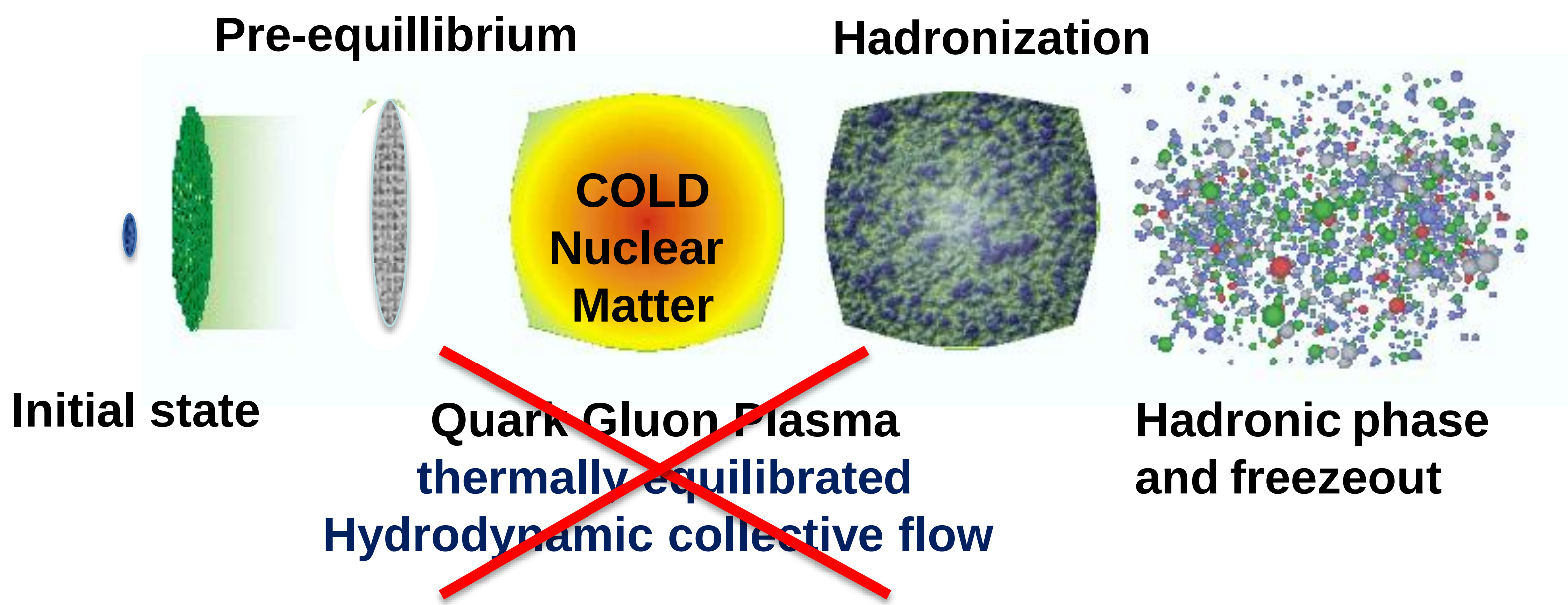


Directed flow of pions in HADES



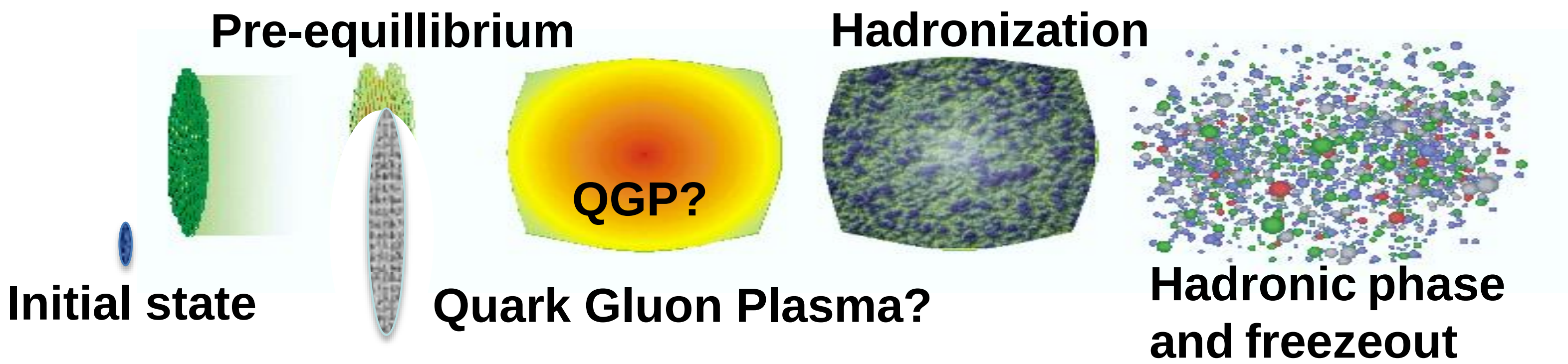


Small colliding systems paradigm



- Not enough particles to achieve equilibration
- The formed medium is expected to be short-lived.
- No QGP
- pp collisions serve as a reference baseline
- pA or dA: reference for cold nuclear matter effects

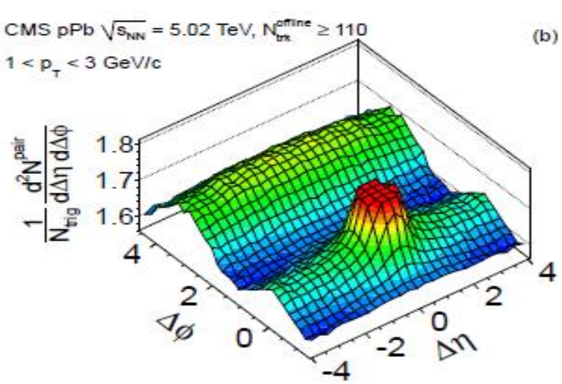
Collectivity in Small Colliding Systems



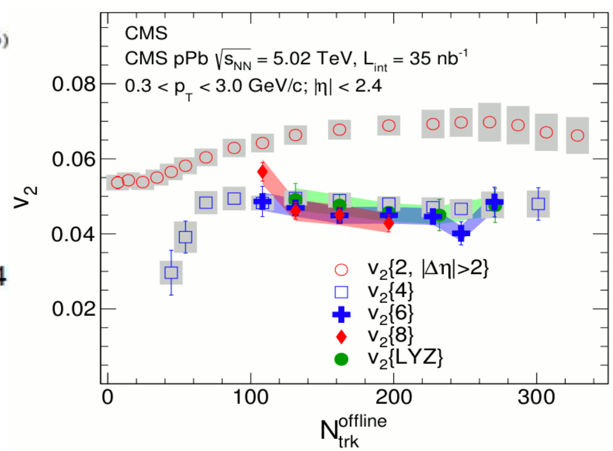
Final state interactions: Hydrodynamic Flow?

Initial momentum correlations: CGC?

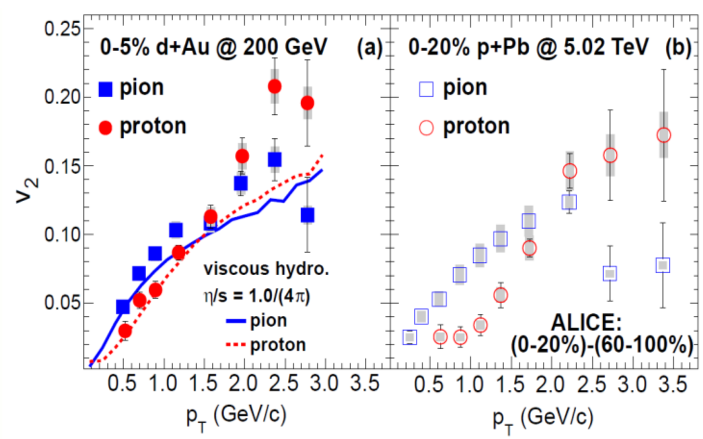
How to distinguish initial vs final state effects ?



PLB 718 (2013) 795

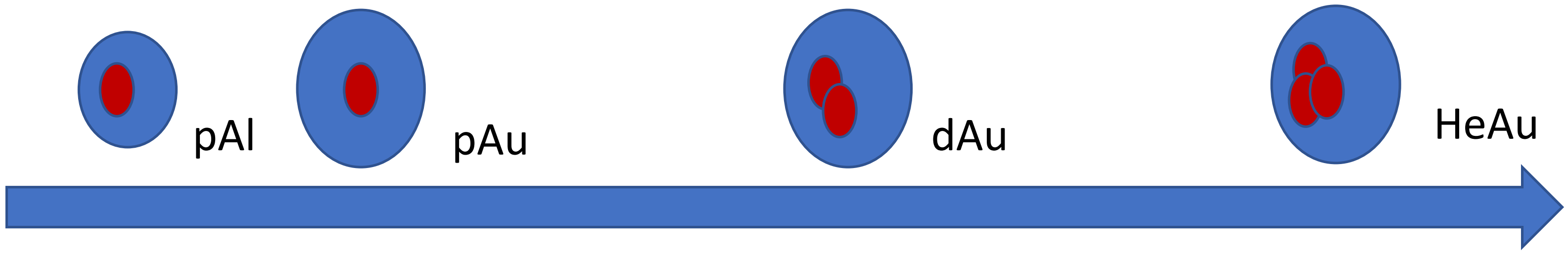


PRL 115 (2015) 012301

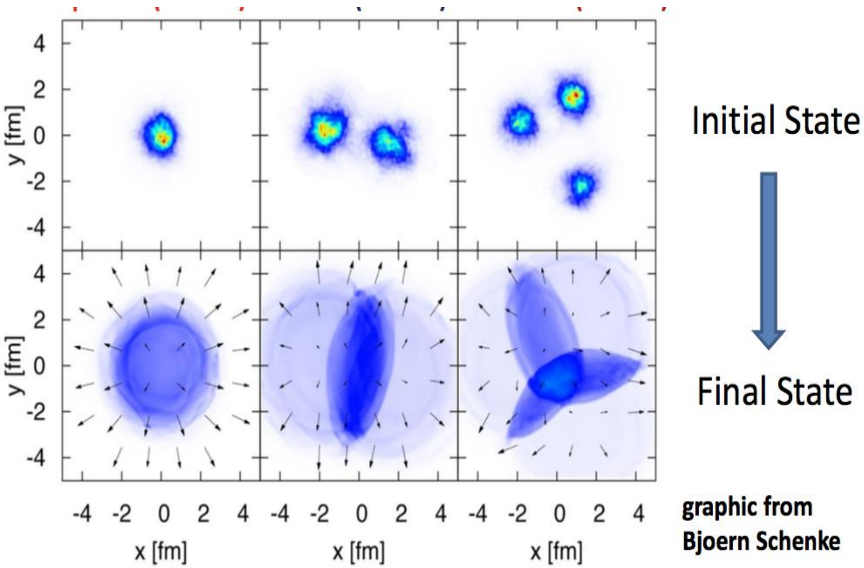


PLB 726 (2013) 164

Small system program at RHIC



Geometry Scan

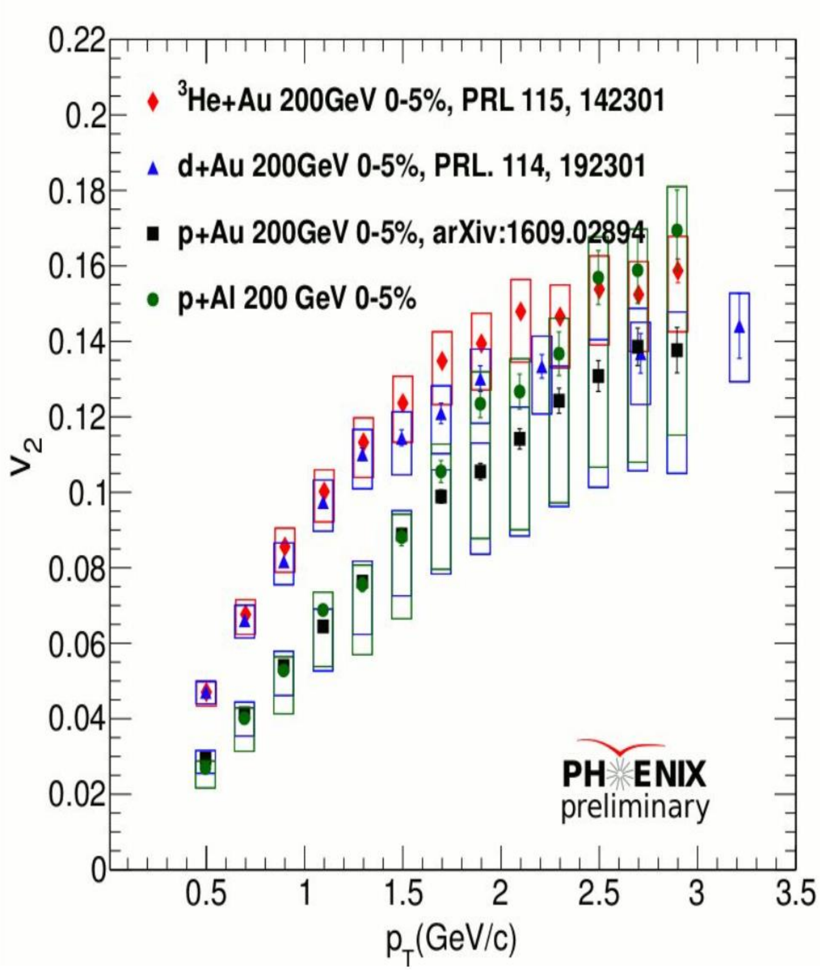


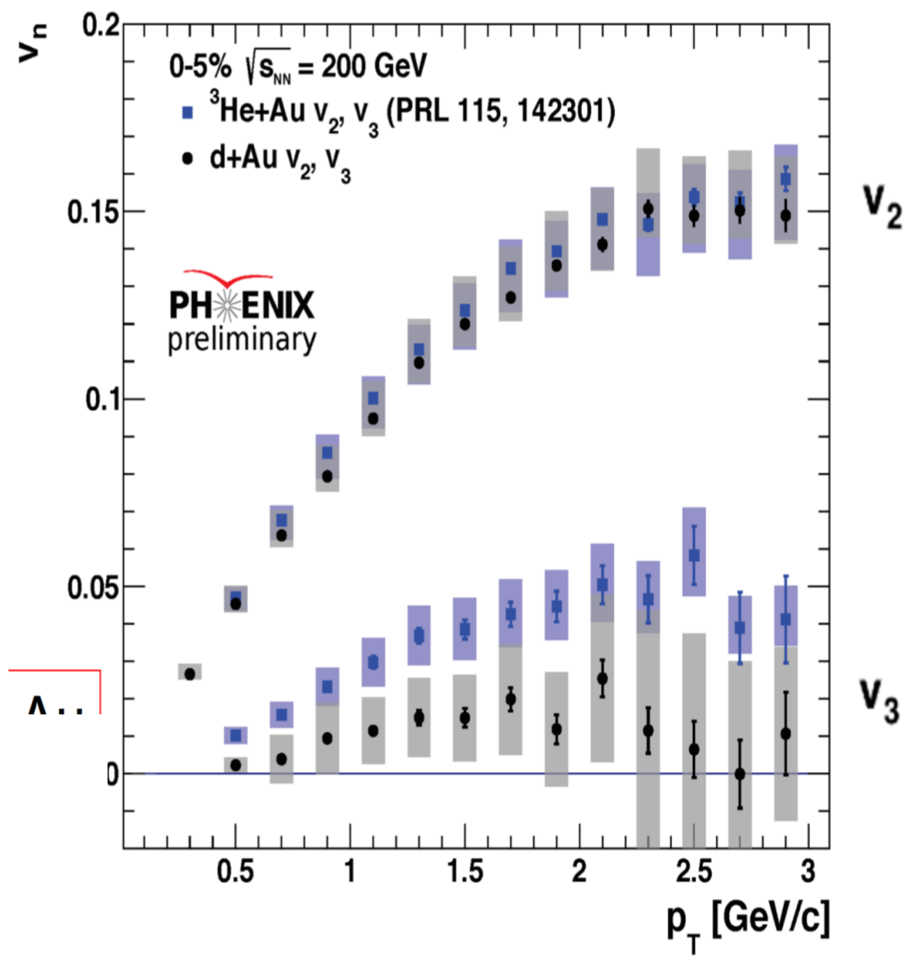
graphic from Bjoern Schenke

	0-5% p+Au	0-5% d+Au	0-5% He+Au
ε_2	0.23	0.54	0.50
ε_3	0.16	0.19	0.28

Different initial geometry → different final state particle emission for p+Au, d+Au and ^{3}He+Au collisions

PHENIX: Vn in small systems (200 GeV)

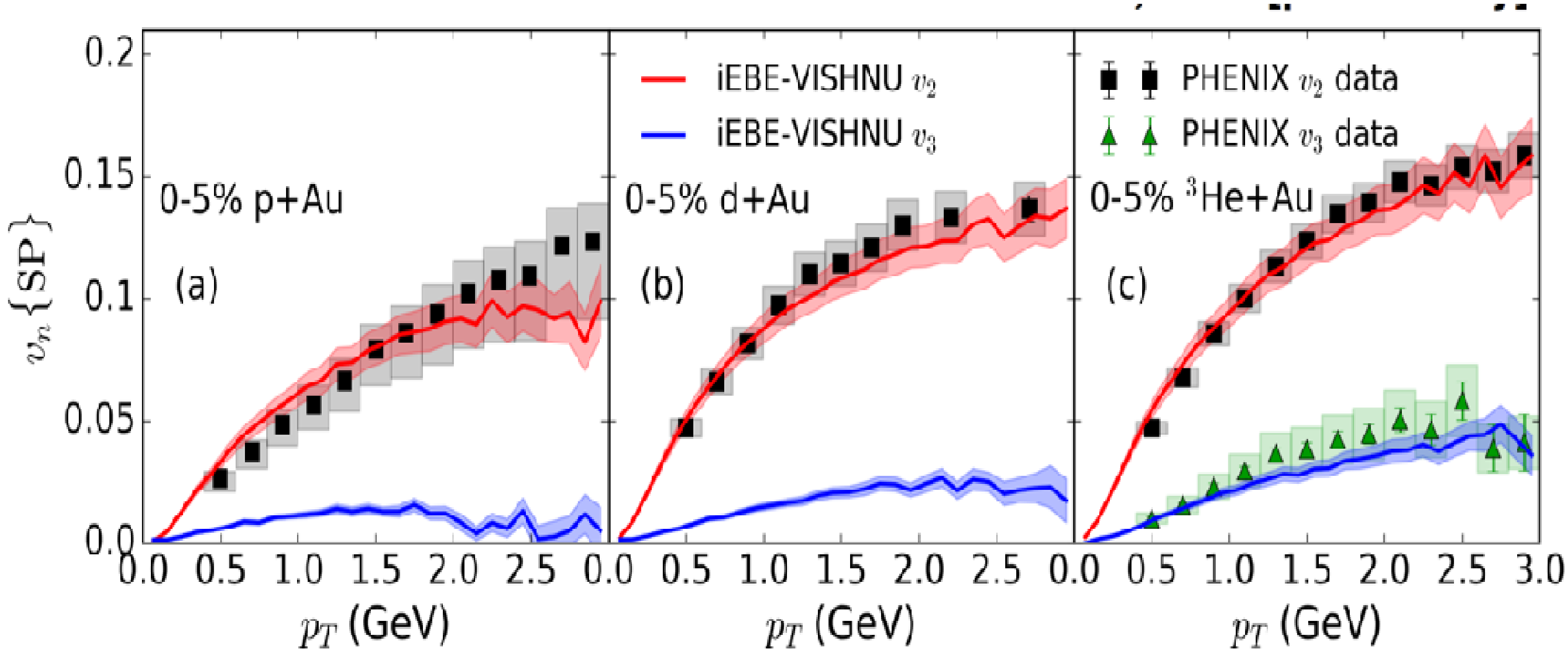




$v_2(^3\text{HeAu}) \sim v_2(\text{dAu}) > v_2(\text{pAu}) \sim v_2(\text{pAl})$ $v_3(^3\text{HeAu}) > v_3(\text{dAu})$

Hierarchy compatible with initial geometry + final state effects

Comparison with viscous hydro calculations



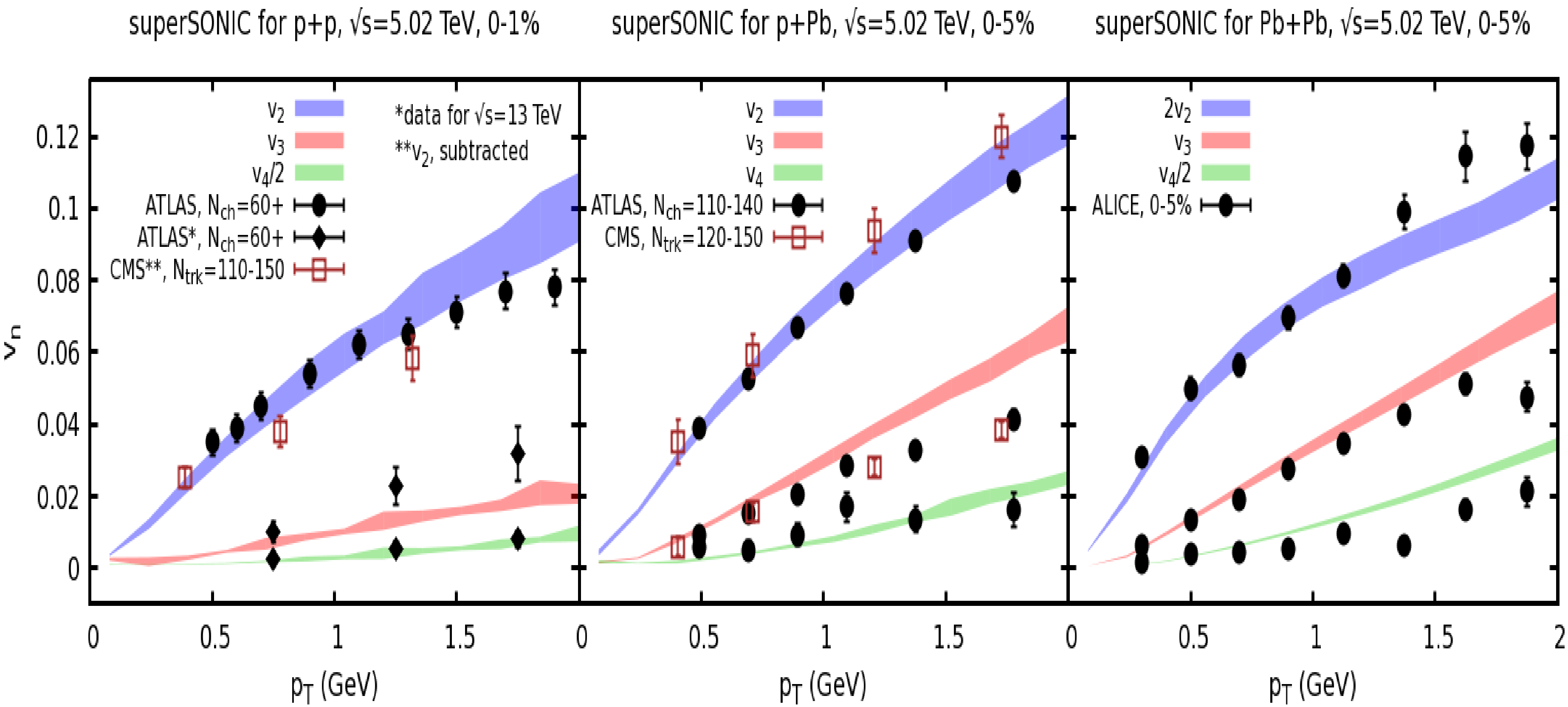
Hydrodynamic response converts spatial gradients into measured momentum anisotropy

C. Shen, *et al.*,

Phys. Rev. C **95**, 014906 (2017)

Indication of a strongly coupled QCD matter?

"ONE FLUID TO RULE THEM ALL"?



Ryan D. Weller, Paul Romatschke

arXiv:1701.07145

Flow is acoustic ! (R.A Lacey (SUNY)

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

- v_n **measurements are sensitive to system shape** (ε_n), **system size** (RT) **and transport coefficients** $\left(\frac{\eta}{s}, \frac{\zeta}{s}, \ldots\right)$.

arXiv:1305.3341
Roy A. Lacey, et al.

- **Acoustic ansatz**
  - ✓ **Sound attenuation in the viscous matter reduces the magnitude of** v_n.
- **Anisotropic flow attenuation,**

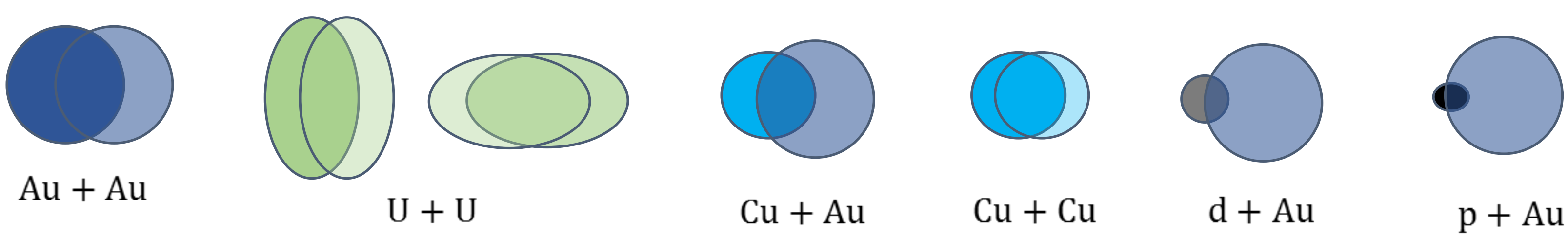
$$\frac{v_n}{\varepsilon_n} \propto e^{-\beta n^2}, \quad \beta \propto \frac{\eta}{s}\frac{1}{RT}$$

arXiv:1601.06001
Roy A. Lacey, et al.

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

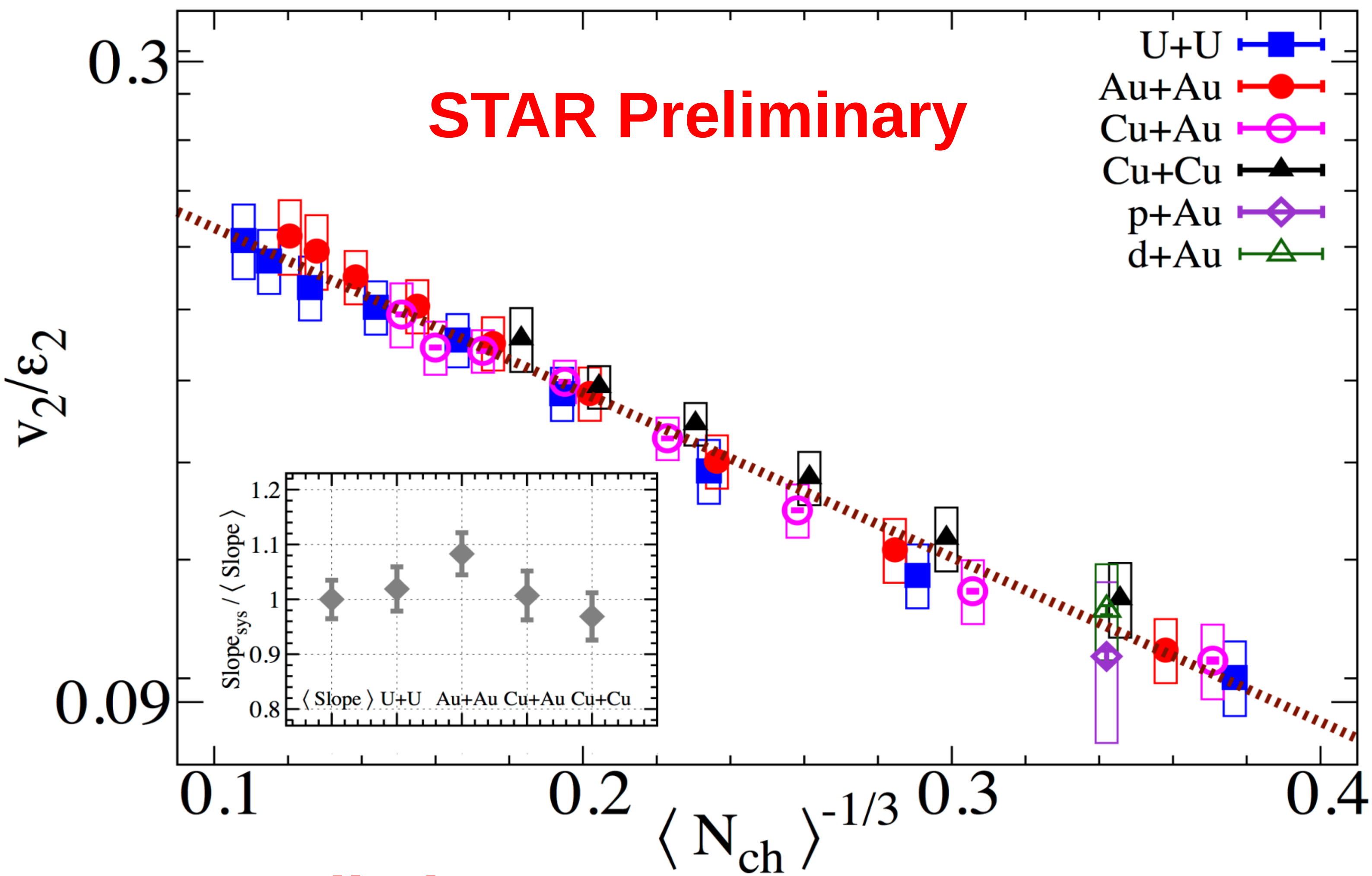
PRC 88, 044915 (2013)
E. Shuryak and I. Zahed

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



Scaling expected For *similar* $\frac{\eta}{s}$ *and* $\frac{dN}{d\eta}$

STAR: V_2 for different colliding systems



STAR Preliminary

MEPhI Heavy-ion physics working group

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.*