Azimuthal Anisotropy in Heavy Ion Collisions

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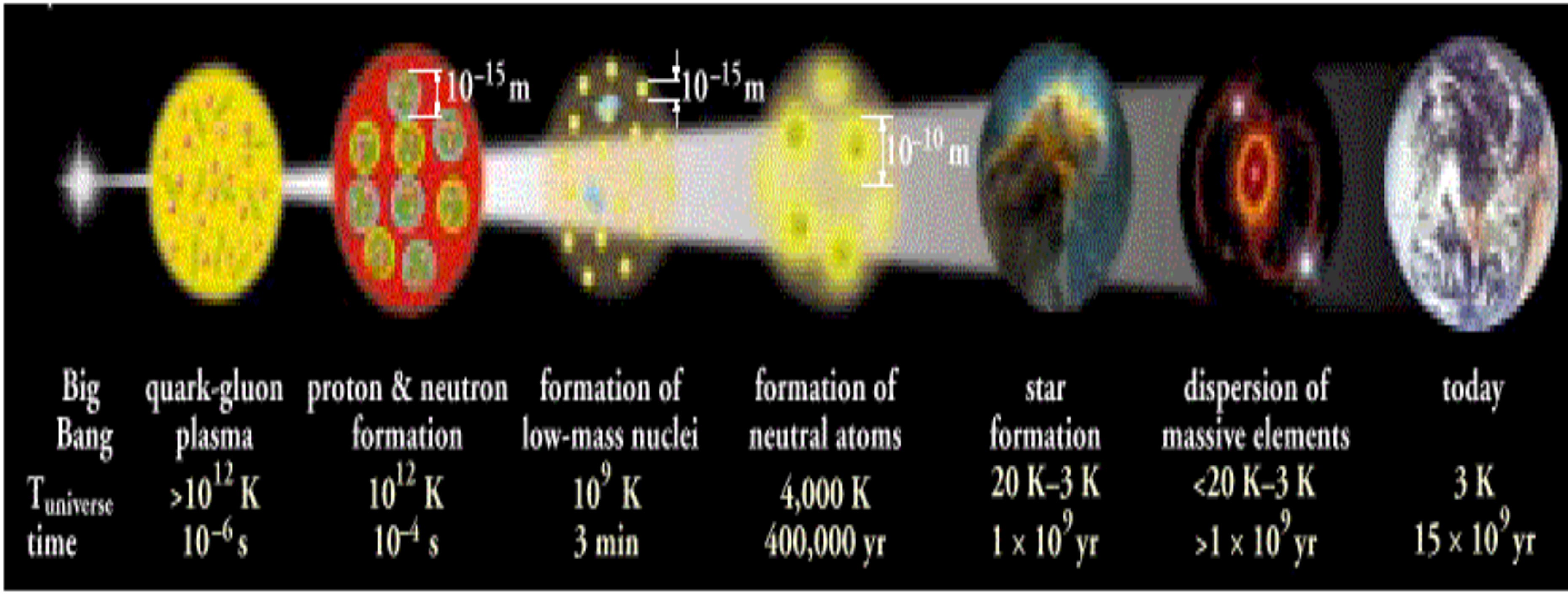
Outline:

- Introduction and Motivation
- Experimental Details
- Results
- Summary and Outlook

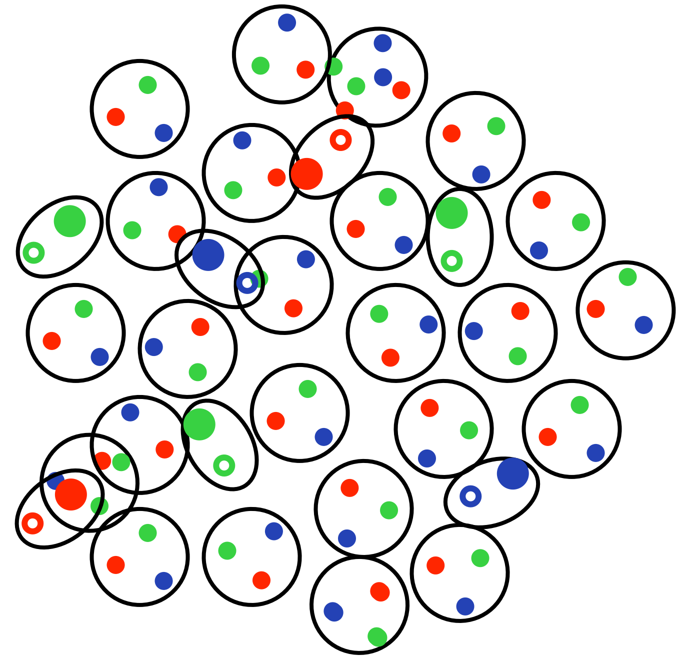
Heavy ion Collisions

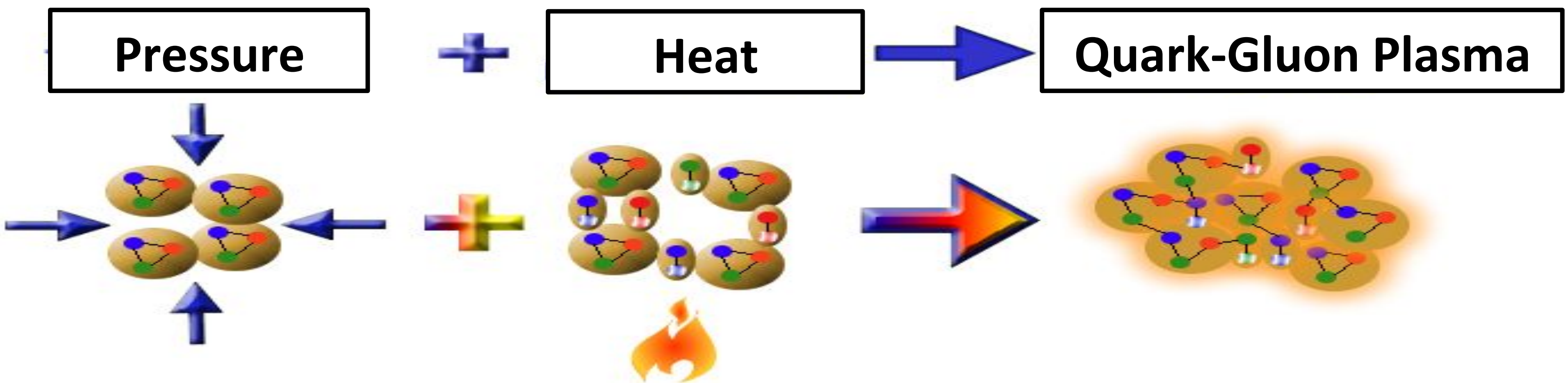


Relativistic Heavy Ion Physics may help to find some of the clues to understand the big picture about the evolution of the universe

Heavy ion Collisions

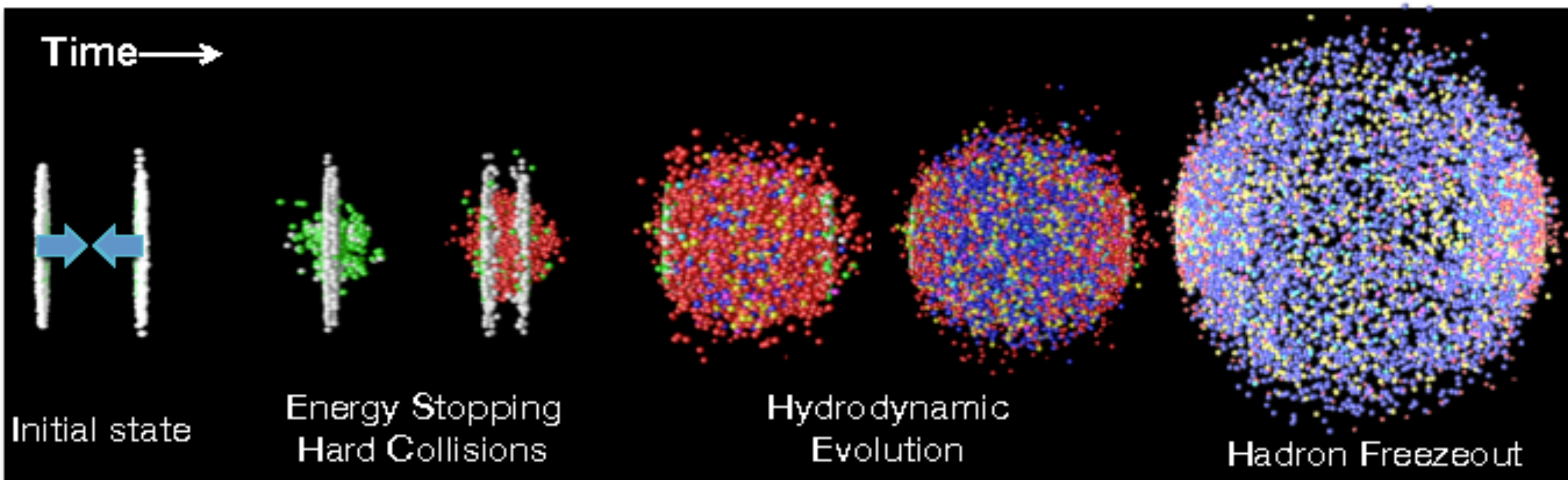
The goal is to create of a system of deconfined quarks and gluons in the laboratory





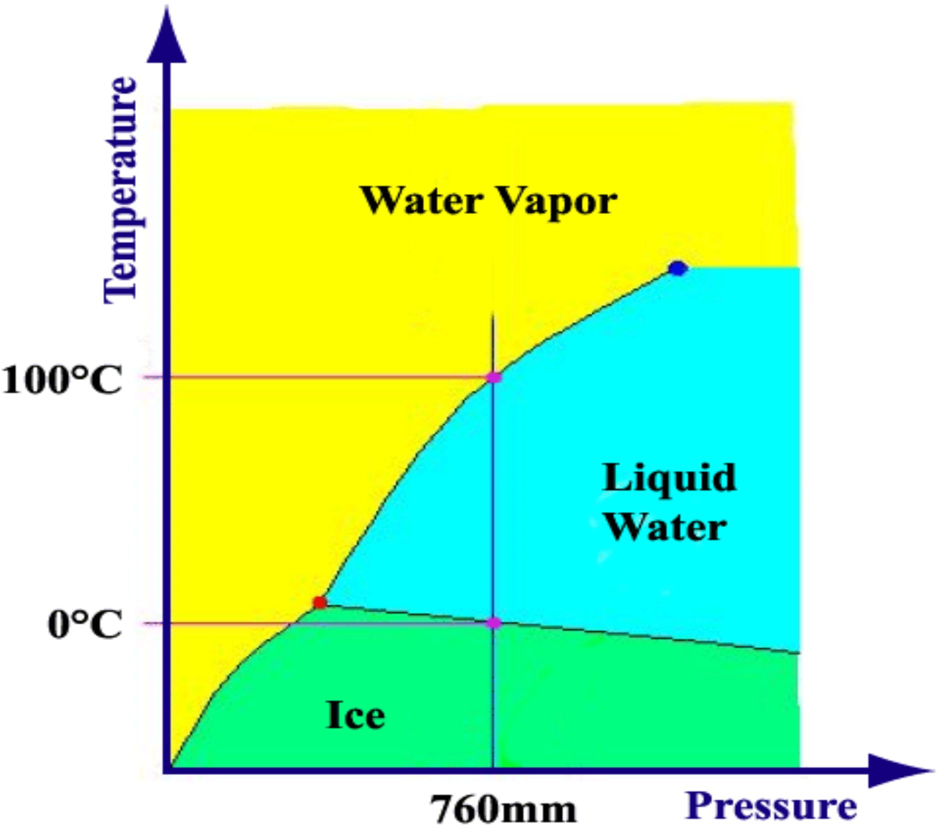
Heavy ion Collisions

- Provide tempreature and compression
- “Melts” the protons and neutrons and, for a brief instant, liberates the quarks and gluons

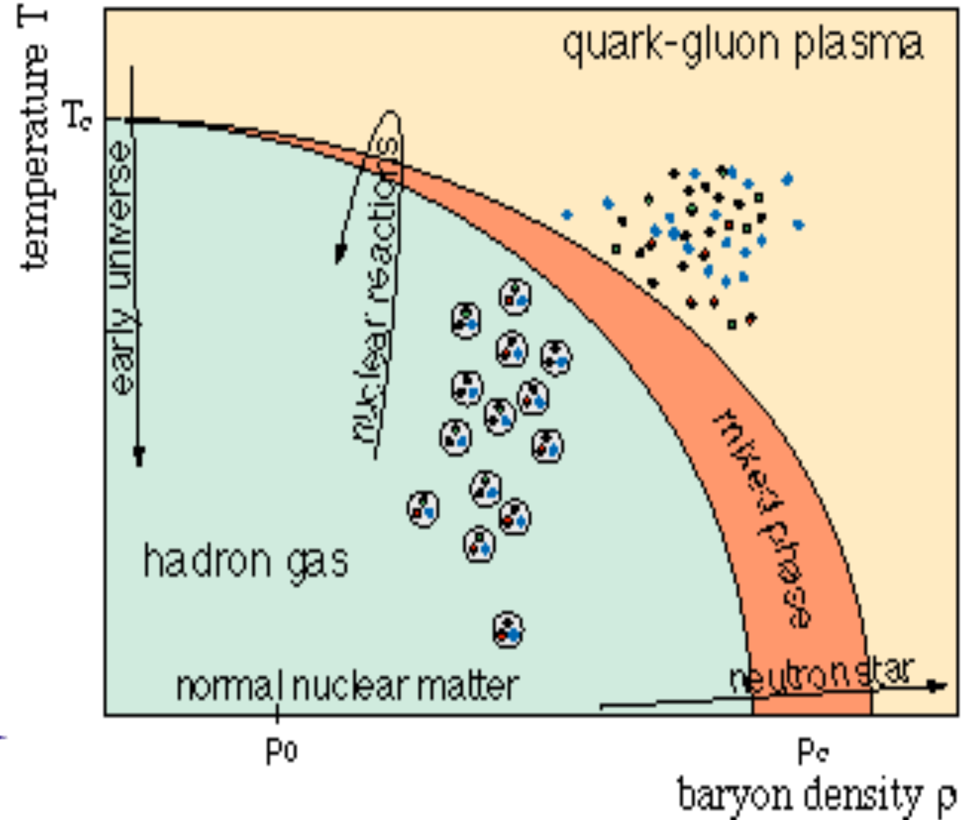


Relativistic heavy-ion collisions are a unique tool to create and study hot QCD matter and its phase transition under controlled conditions

Heavy ion Collisions



Water

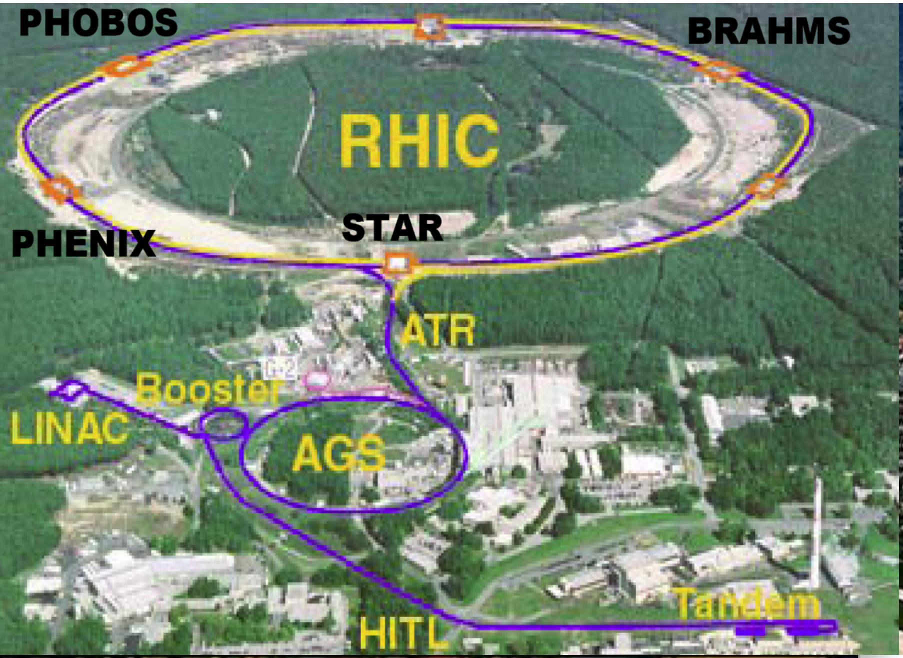


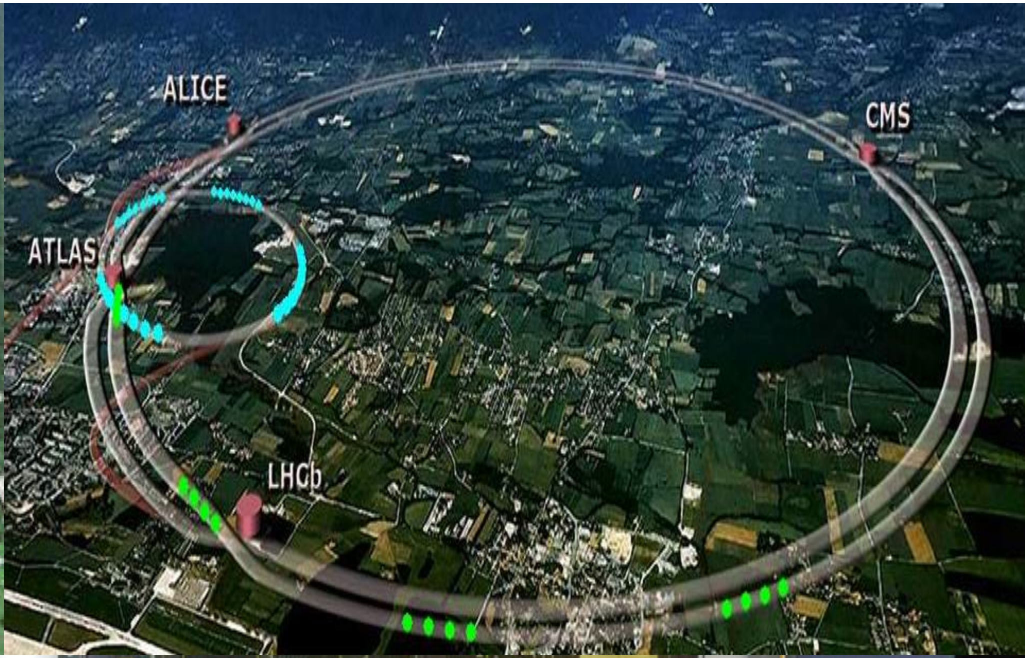
Nuclear Matter

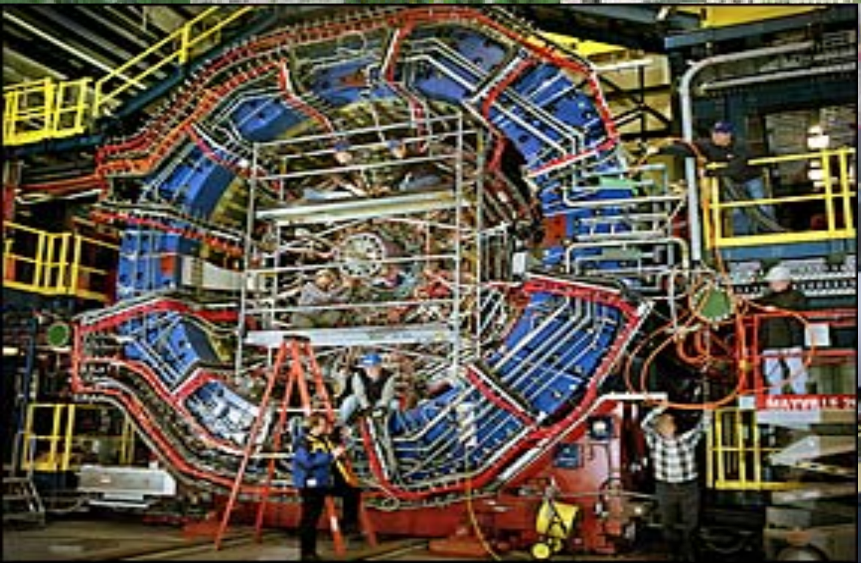
The QCD phase diagram: structure of matter with quark- and gluon-degrees (color degrees) of freedom.

Experimental exploration of the QCD phase diagram to understand the fundamental theory through its phase structure

QGP Laboratory: Heavy Ion Collidiers





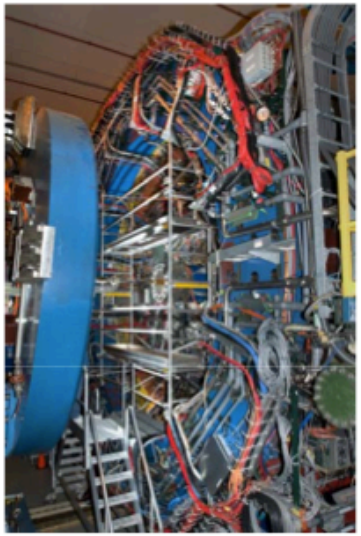


Heavy Ion Experiments

RHIC

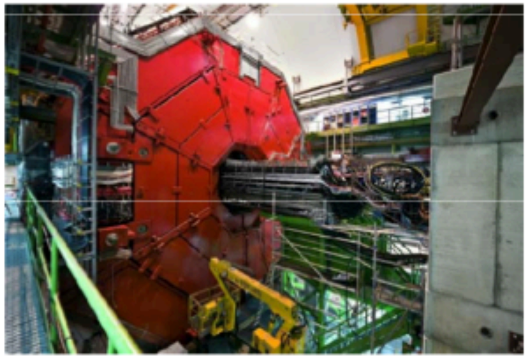
- PHENIX

- STAR

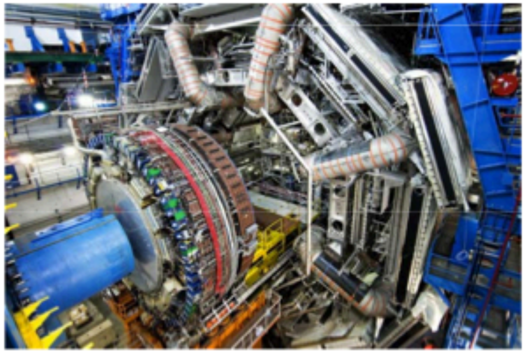


LHC

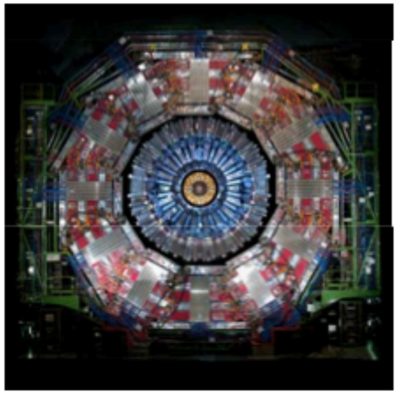
- ALICE



- ATLAS

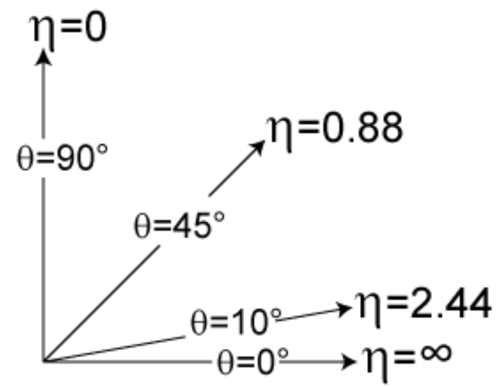


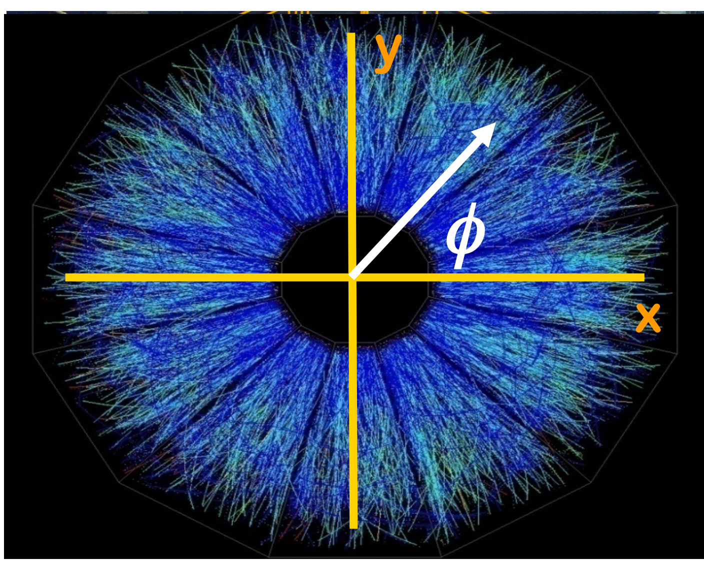
- CMS

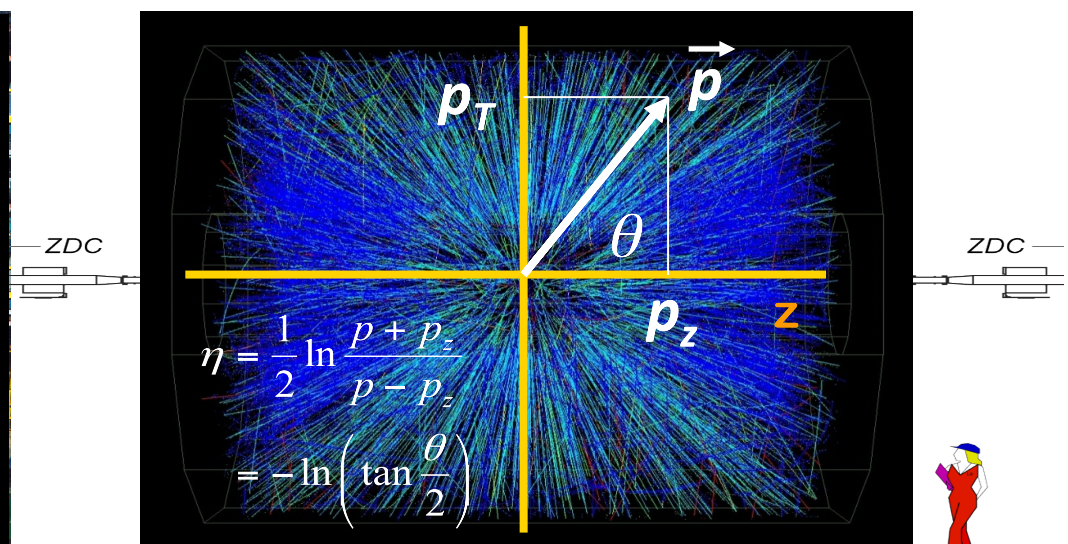


Heavy Ion Experiments

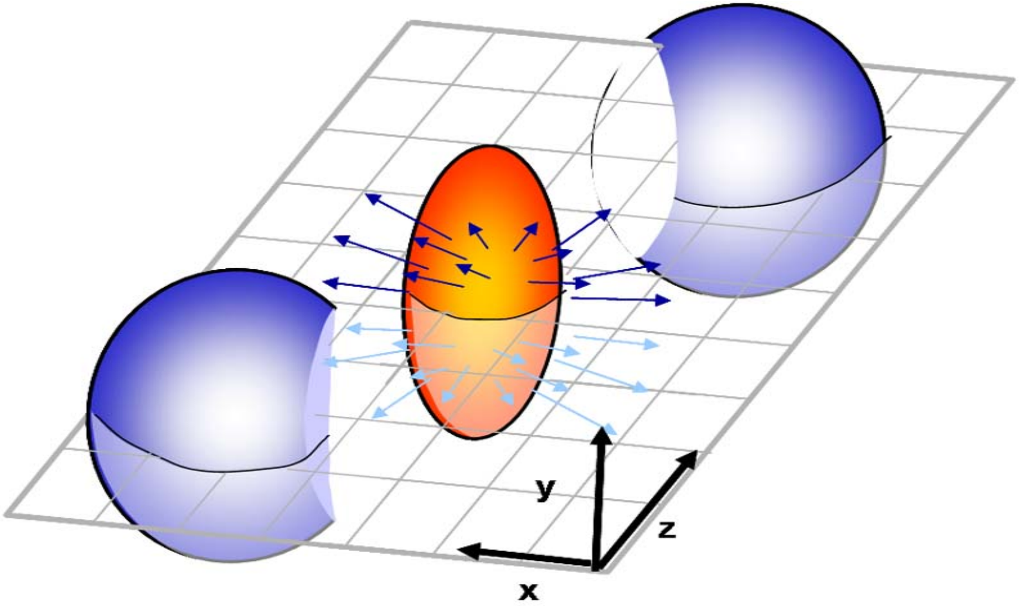
- Cannot directly observe QGP
- Instead, analyze outgoing hadrons
- Focus: Momentum in suitable coords
- Observables are yields, single-particle spectra and correlations between hadrons

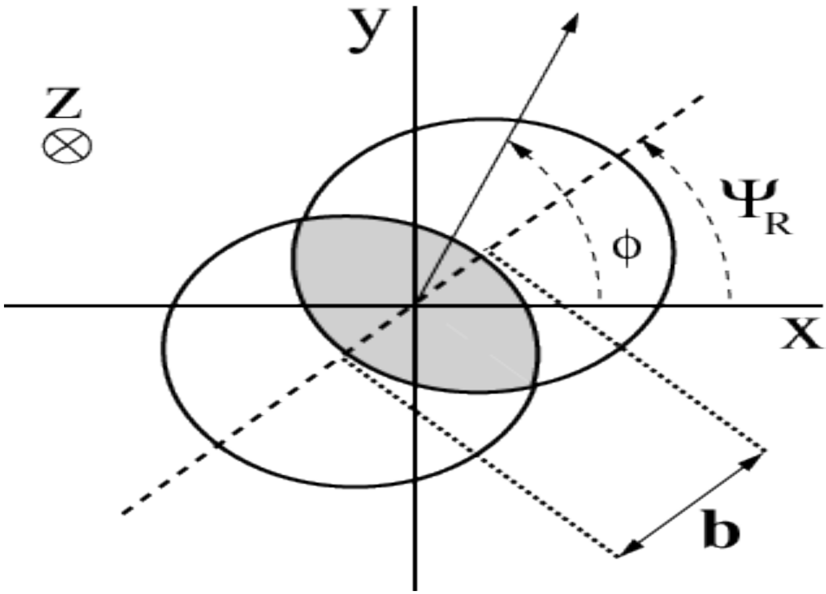






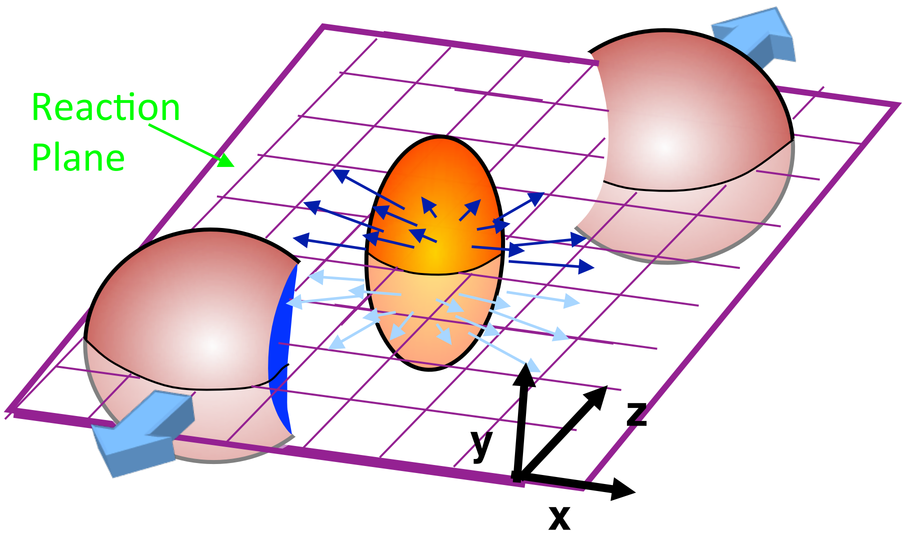
Reaction Plane

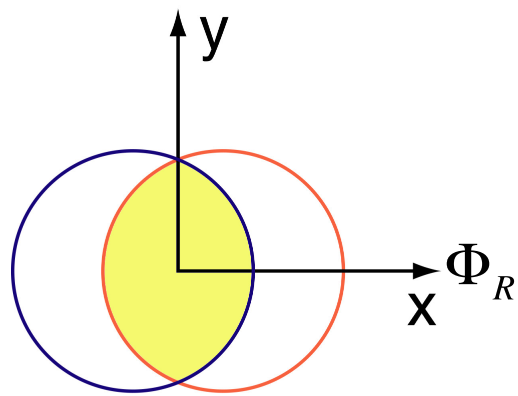




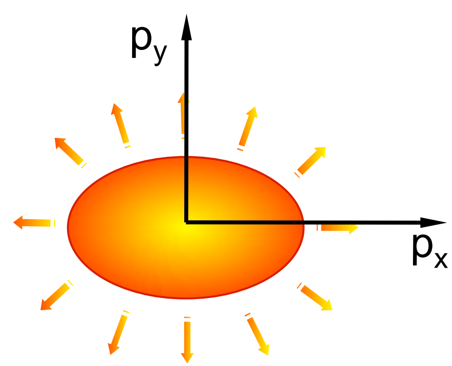
- Reaction plane provides natural coordinate system in non central collisions
- Experimentally the reaction plane Ψ_r is <u>unknown</u>
- Experimental estimater of the reaction plane is event plane
- Anisotropic flow ≡ azimuthal correlation with the reaction plane

Azimuthal Anisotropy





Spatial anisotropy(ε_n)



Momentum anisotropy(v_n)

Azimuthal distribution of particles with respect to the reaction plane is given by:

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

$$v_n = \left\langle \cos\left[n\left(\varphi - \psi\right)\right]\right\rangle$$

S. A. Voloshin and Y. Zhang, Z. Phys. C 70, 665 (1996), J.-Y. Ollitrault, Nucl. Phys. A590, 561c (1995), A. M. Poskanzer and S. A. Voloshin, Phys. Rev. C 58, 1671–1678 (1998)

Azimuthal Anisotropy

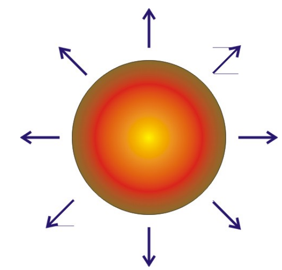
$$E\frac{dN^3}{d^3p}=\frac{1}{2\pi}\frac{d^2N}{p_t dp_t dy}\left(1+2v_1\cos(\phi-\psi_R)+2v_2\cos 2(\phi-\psi_R)+\ldots\right)$$

isotropic directed elliptic

Radial flow

Isotropic expansion of participant zone

Measurable via slope parameter of spectra

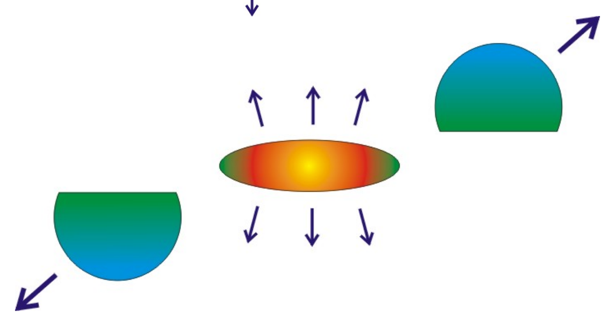


Directed flow (v_1)

Spectators deflected from dense reaction zone

Sensitive to pressure

Strong sensitivity to EoS

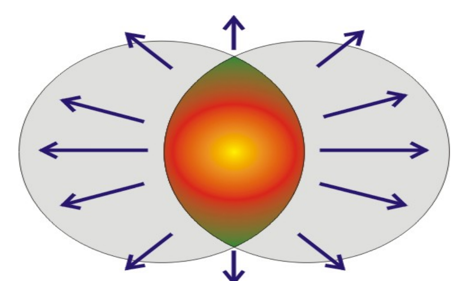


Elliptic flow (v_2)

Asymmetry out- vs. in-plane emission

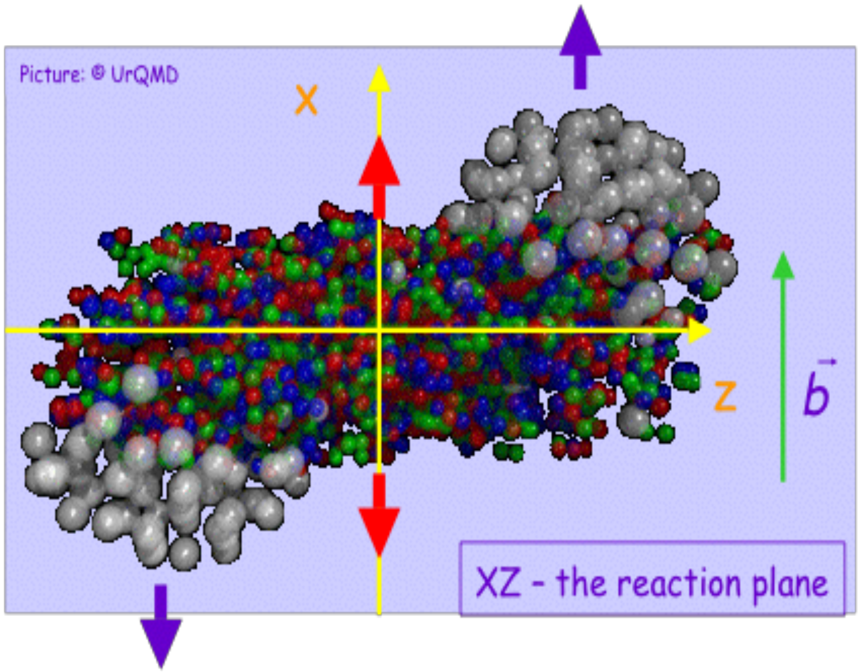
Emission mostly during early phase

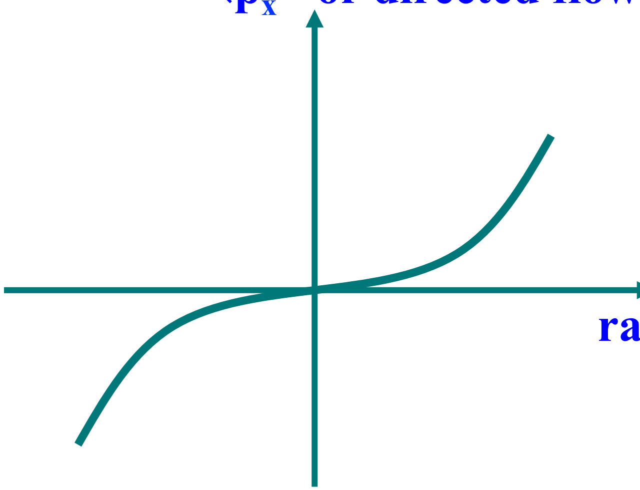
Sensitive to EoS



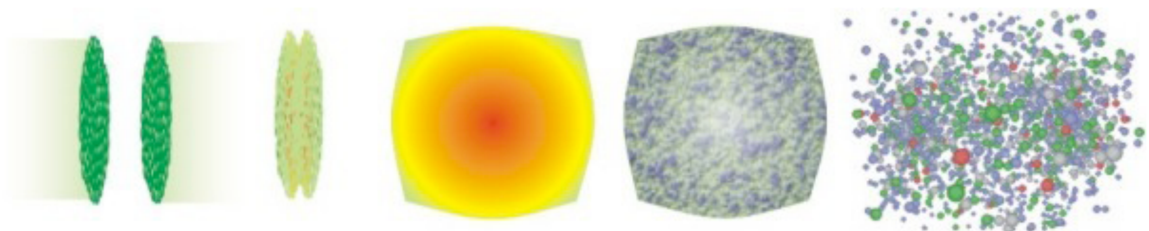
Directed flow (v_1)

Directed flow is quantified by the first harmonic (v_1)





-The directed flow (v_1) is generated during the nuclear passage time ($2R/\gamma$ ~ 0.1 fm/c) and therefore it probes the foremost early stage collision dynamics.



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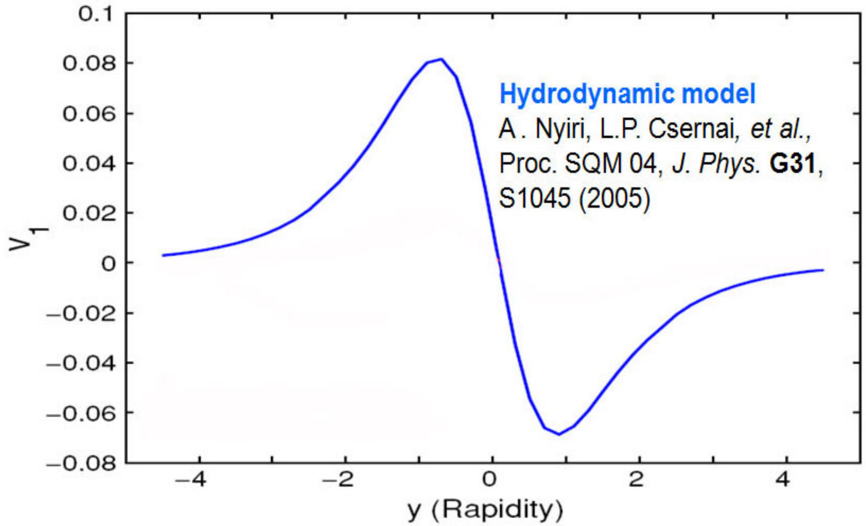
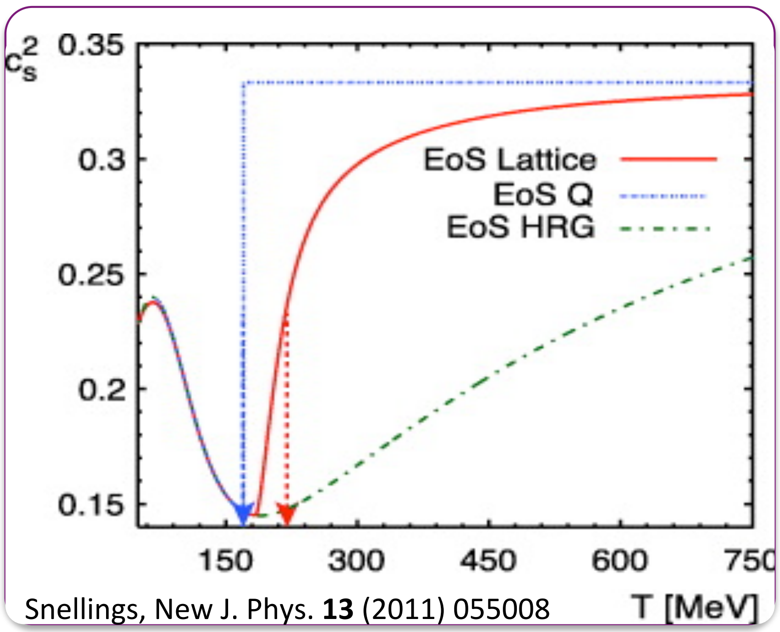
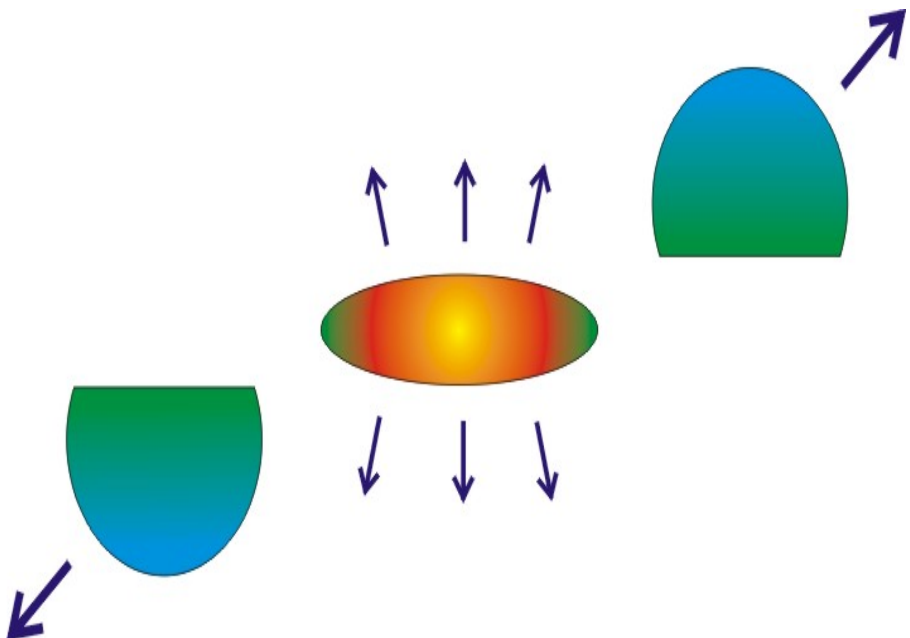
Directed flow

- First form of flow predicted (one-fluid hydro) and observed (Plastic Ball) in 1980's
- sensitive to pressure
- Hydro with QGP phase transition shows wiggle
- traditionally less focus on v_1 at higher energies, where
  - signal is small
  - v_2 stole the limelight





Snellings, New J. Phys. **13** (2011) 055008



What drives directed flow?

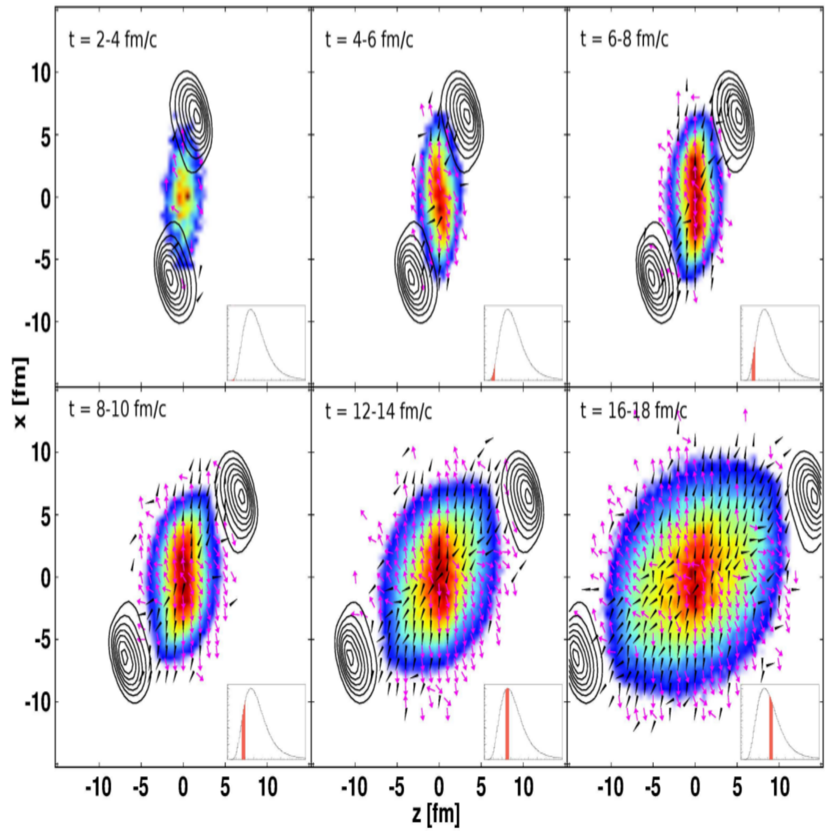
Most models at high energy suggest emission from a "tilted disc".

- **Antiflow of Nucleons at the Softest Point of the EoS Brachmann et al, Phys.Rev. C61 (2000) 024909 nucl-th/9908010**

- **Scaling violation of transverse flow in HIC at AGS Bravina, PLB 344 (1995) 49**
- **Directed flow in ultrarelativistic heavy-ion collisions Bozek and Wyskiel PHYSICAL REVIEW C 81, 054902 (2010)**

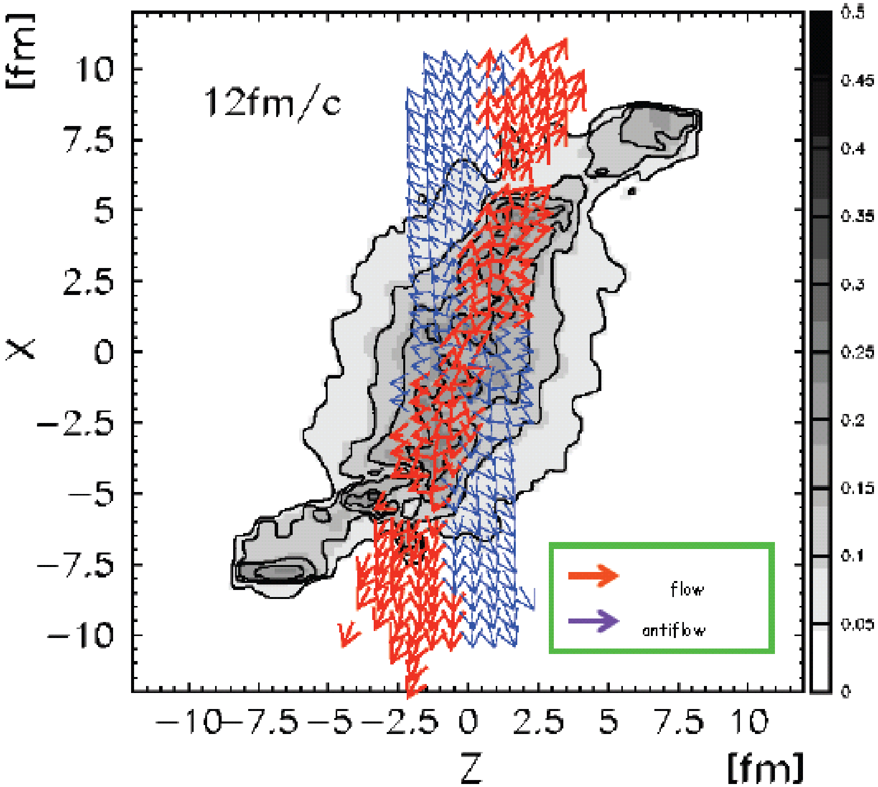
- **Effective string-rope model... Magas, Csernai, Strottmann Nucl.Phys. A712 (2002) 167-204 arXiv:hep-ph/0202085**

- **A twisted emission geometry in non-central Pb+Pb collisions measurable via azimuthally sensitive HBT Graef, Lisa, Bleicher sub PRC arXiv:1302.3408**

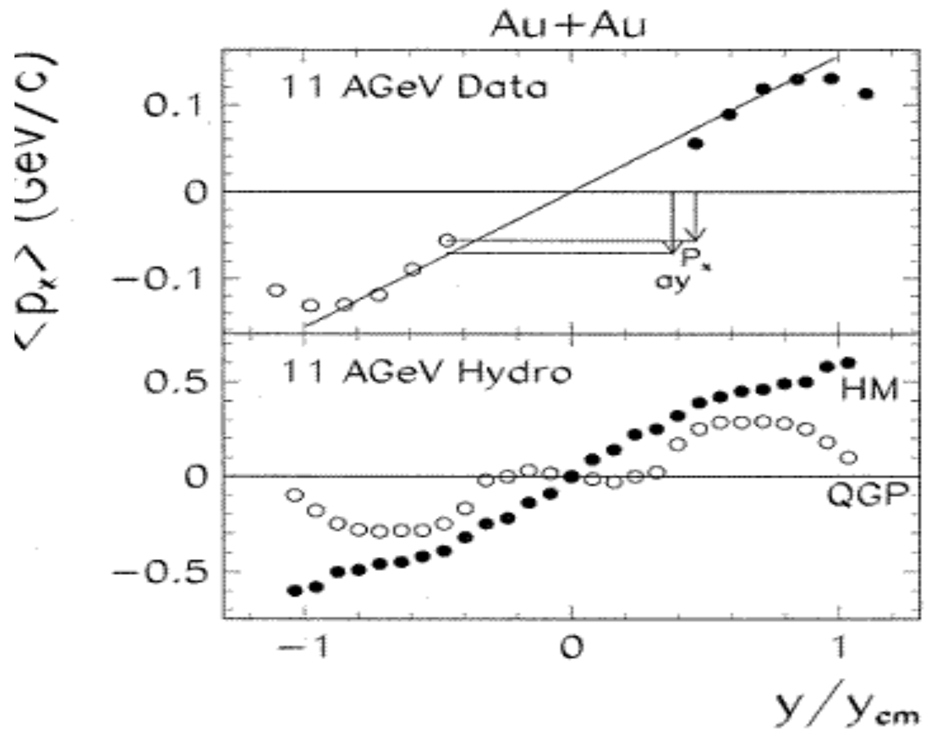


.. that must certainly evolve non-trivially with time

Directed flow: Protons and Pions



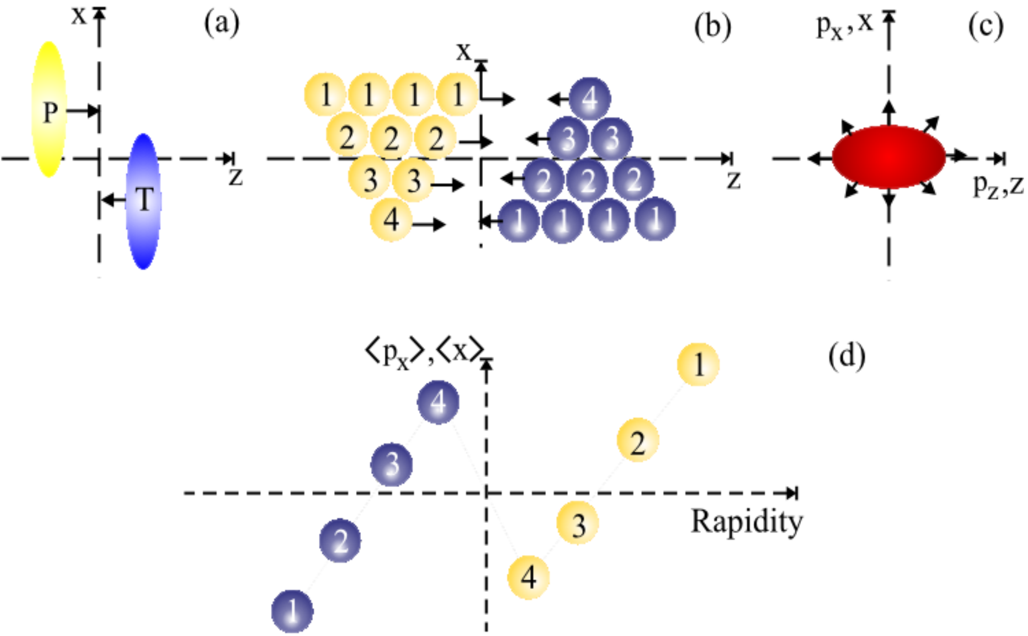
J. Brachmann et al., PRC 61, 24909 (2000).

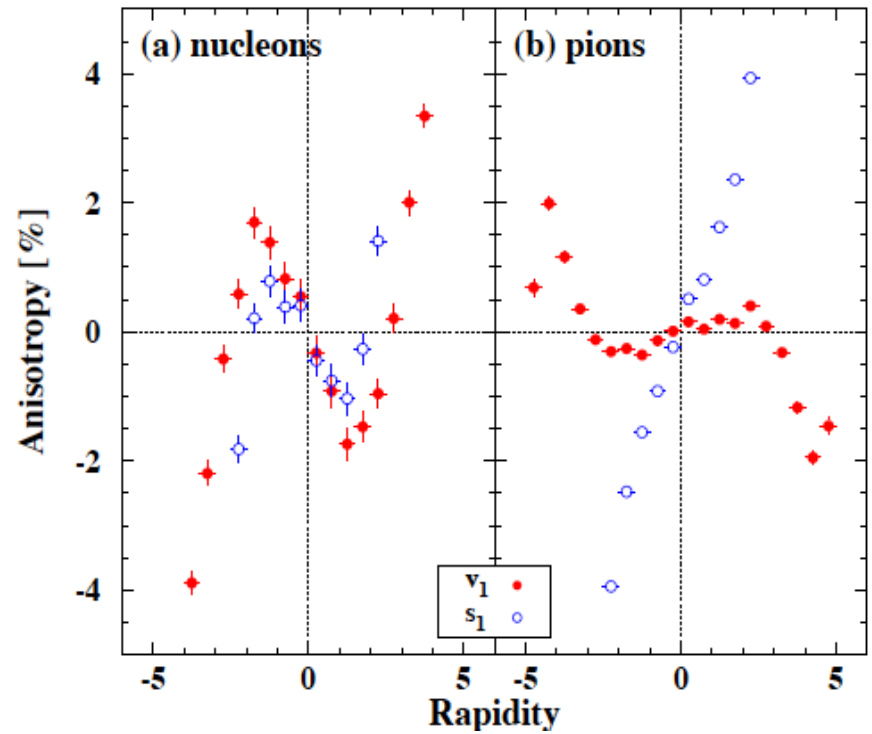


L.P. Csernai, D. Rohrich PLB 458, 454 (1999)

Anti-flow/3rd flow component: $v_1(y)$ crosses zero 3 times (so-called "wiggle") or flat v_1 at midrapidity due to 1^{st} order phase transition.

Directed flow: Protons and Pions





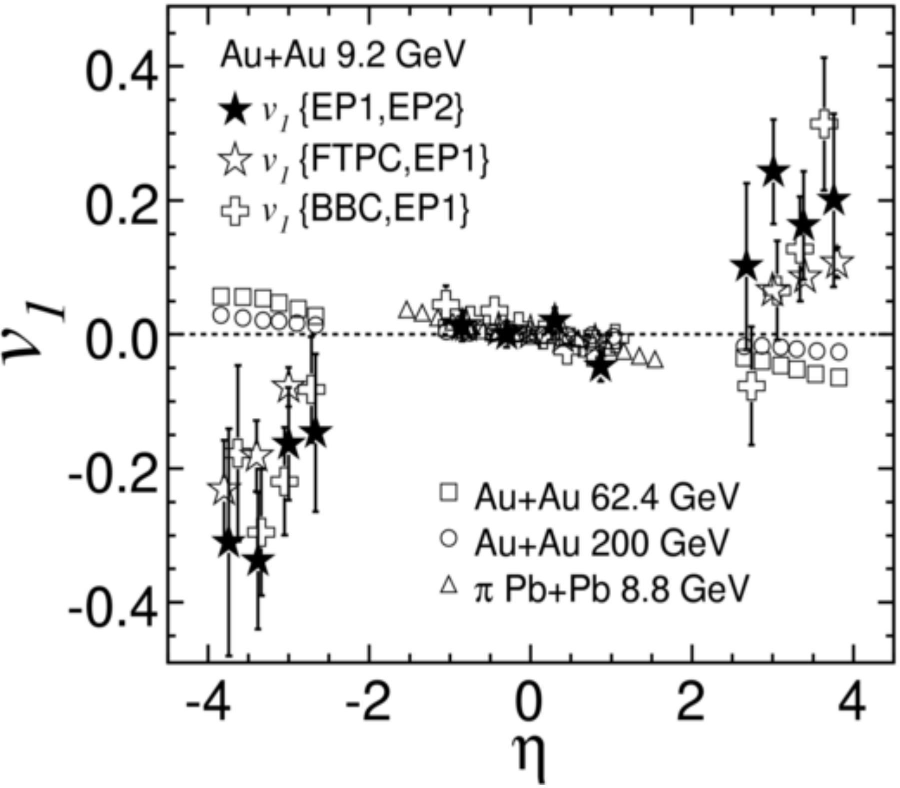
R. Snellings, H. Sorge, S. Voloshin, F. Wang, N. Xu, PRL **84** 2803 (2000)

Baryon stopping +positive space-momentum correlation may also give wiggle structure in v_1: NO QGP necessary

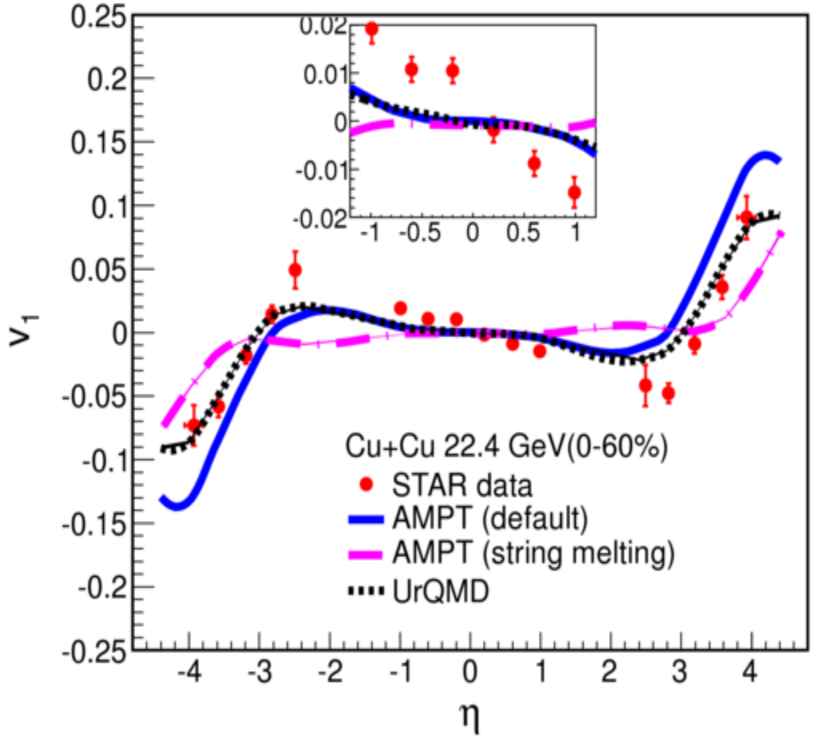
M. Bleicher and H. Stöcker, PLB 526, 309 (2002)

Directed flow(v_1)

STAR: Phys. Rev. C 81 (2010) 24911

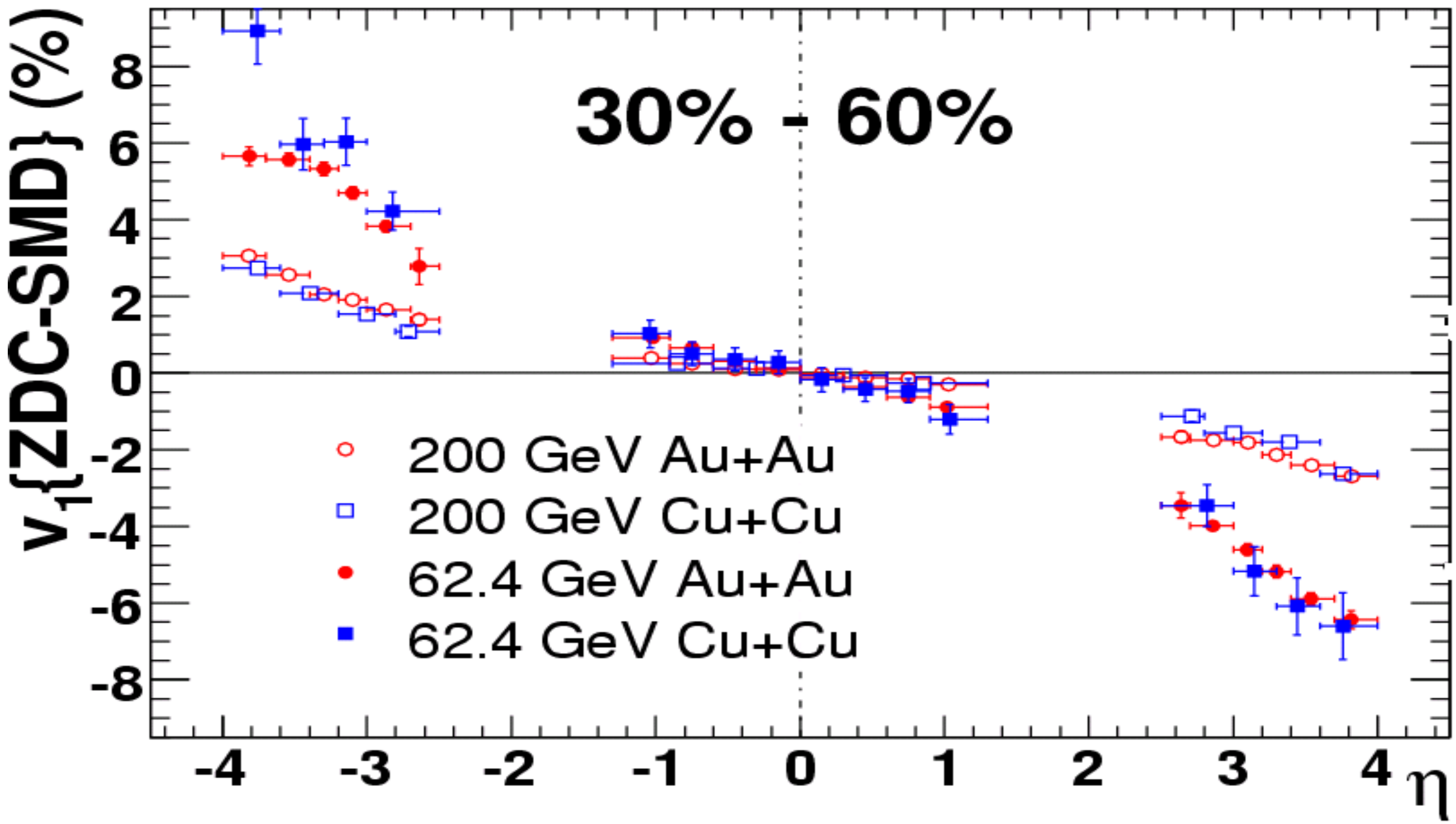


STAR: Phys. Rev. C 85 (2012) 14901



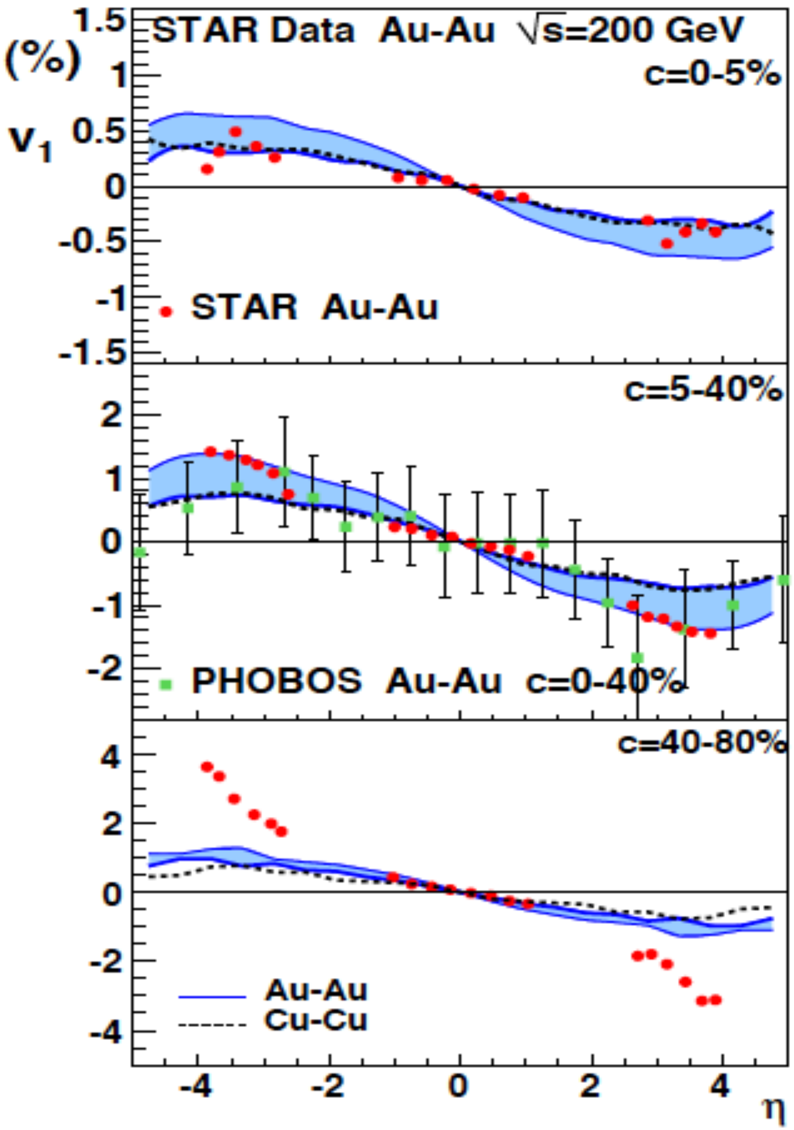
Directed flow of Charged particles measured by STAR Collaboration

Directed flow

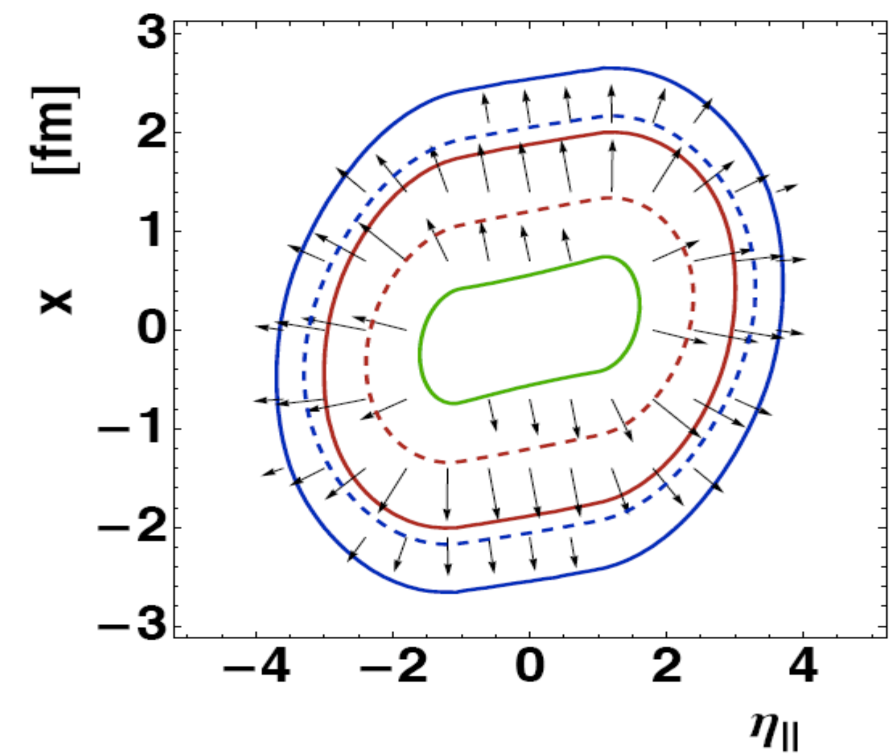


At 62.4 & 200 GeV, no difference within errors between AuAu & CuCu

Directed flow

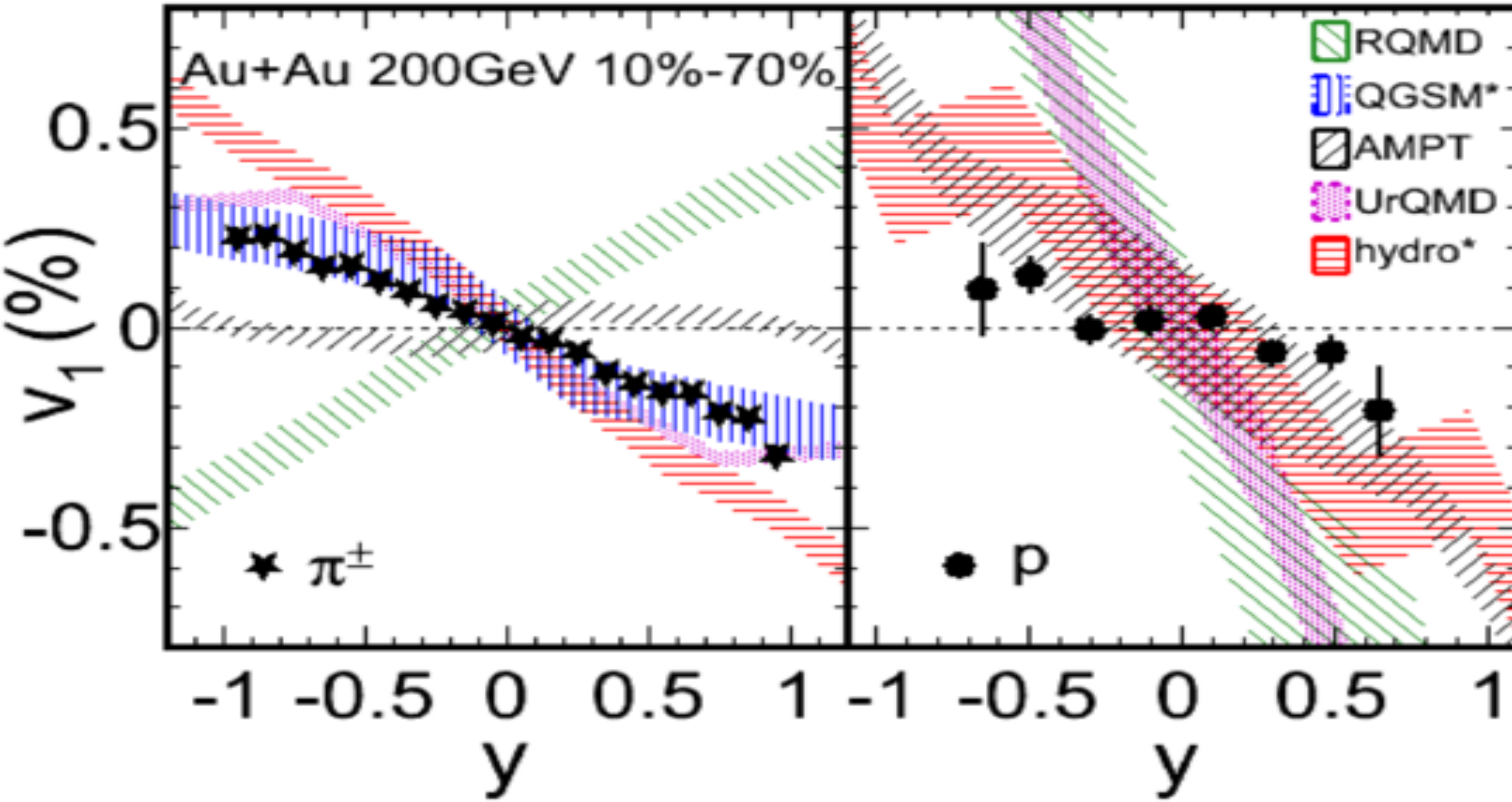


Bozek and Piekarska, PRC 81, 054902 (2010)



System-size independence can be explained by Hydro+tilted source

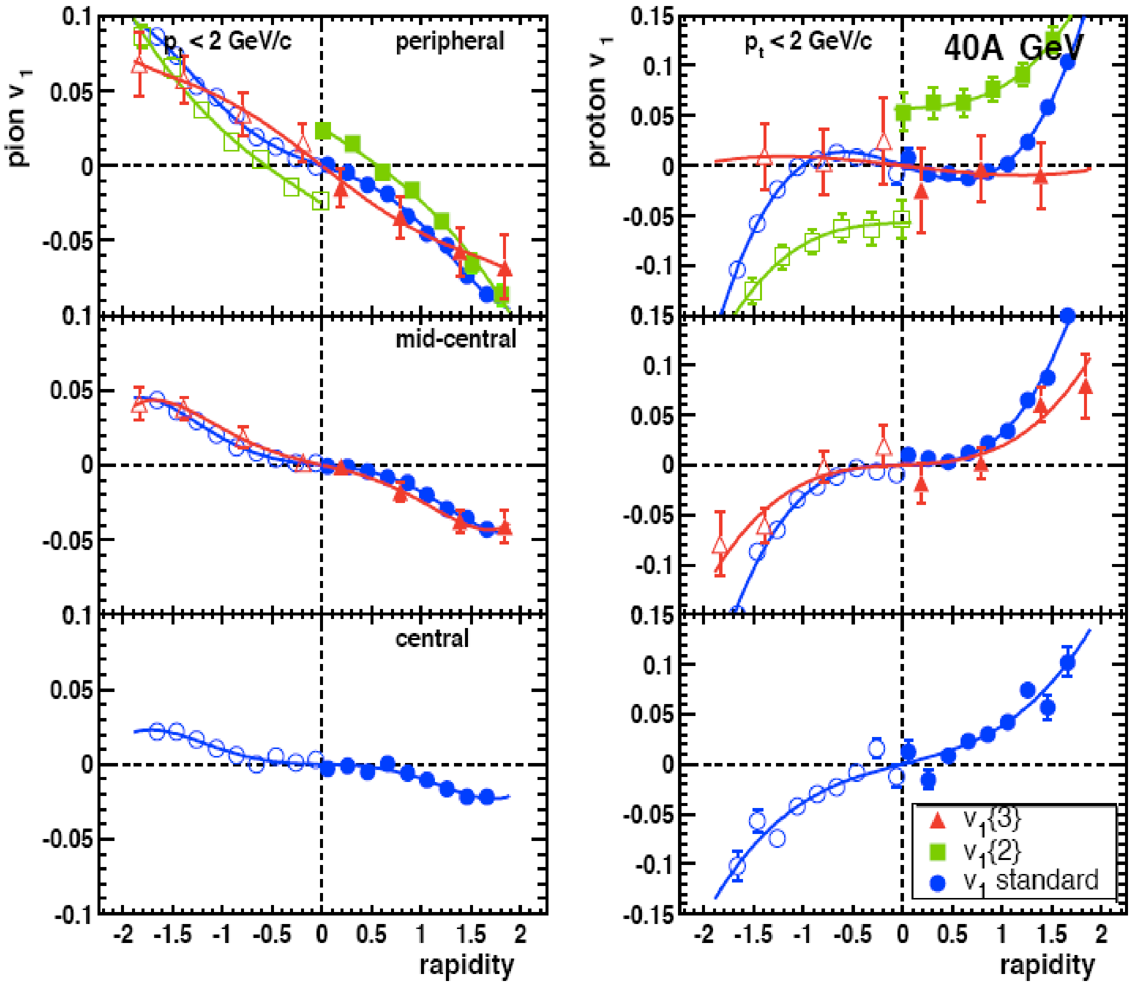
Directed flow: Protons and Pions



None of models can describe $v_1(y)$ for pions an protons simultaneously: STAR PRL 108 (2012) 202301

Directed flow of pions and protons at SPS energies

NA49, Phys. Rev. C 68, 034903 (2003)



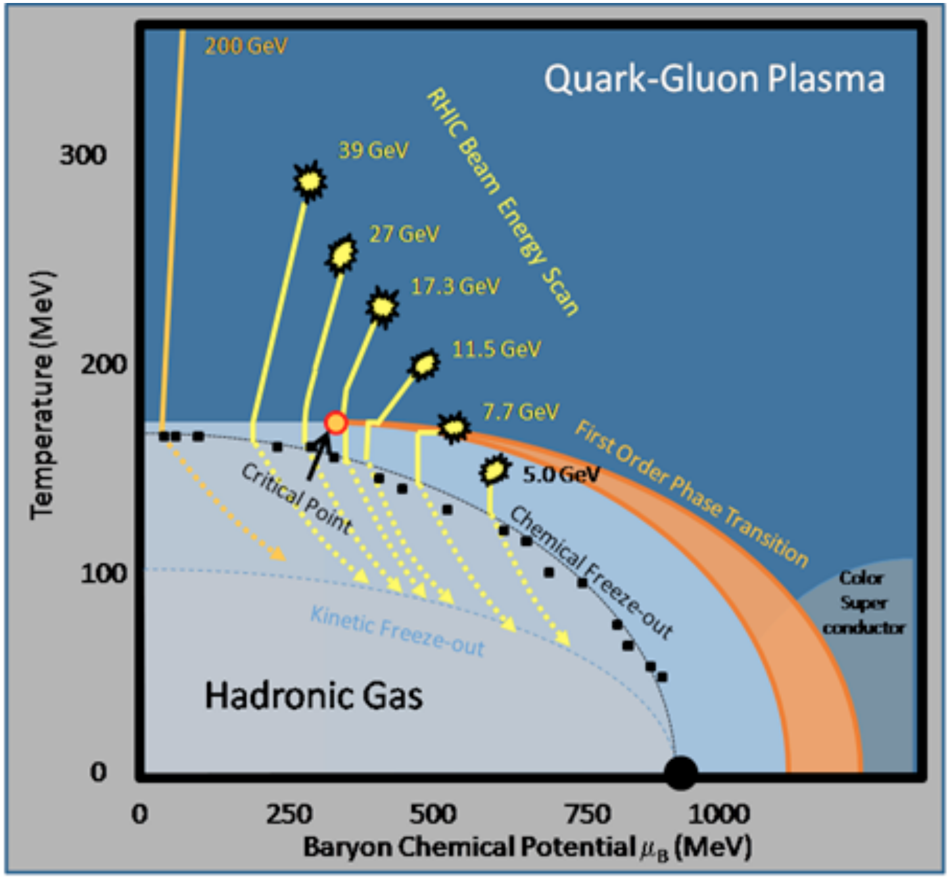
- Negative v_1 slope for pions for all centralities
- Positive v_1 slope for proton at cnetral and mid central collisions.
- Protons slope at peripheral collisions becomes flat.

In peripheral collisions spectators shadowing can mimic the formation of the quark-gluon plasma (QGP)

L.V. Bravina et. Al PLB, 470(1999)

All panels above refer to Pb+Pb at $\sqrt{s_{NN}}$ = 8.8 GeV

Exploring QCD Phase Diagram: STAR BES-I



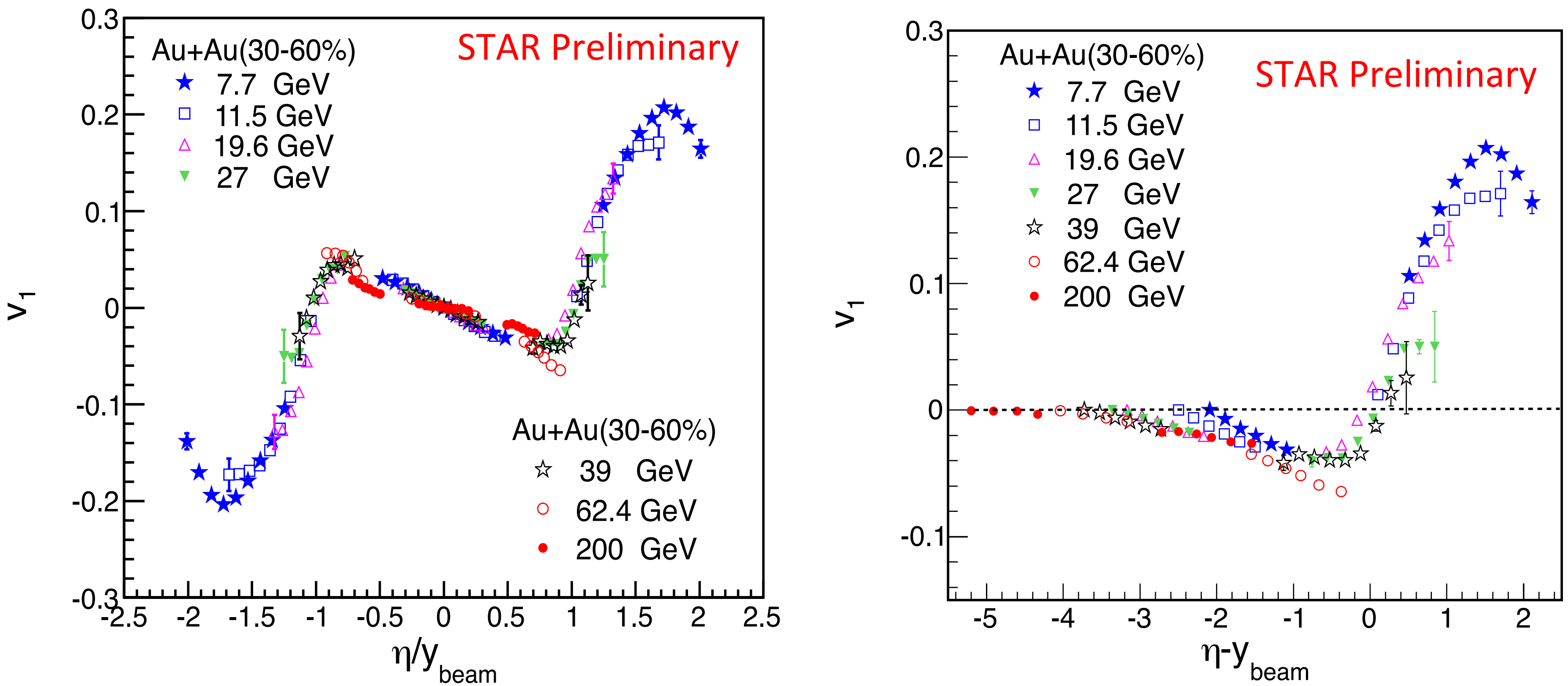
- Only a part of this phase diagram is known
- In the intermediate T and μ_B region, experiment exploration are the best hope to find
  - location on the phase diagram
  - sQGP signatures turn off/on
  - evidence of mixed phase
  - critical fluctuations

Directed flow : A key observable first order phase transition

year	$\sqrt{s_{NN}}$ (GeV)	μ_B	mb events ($x10^6$)
2010	7.7	420	5
2011	11.5	315	12
2011	19.6	205	36
2010	27	155	70
2010	39	115	130

Directed flow(v_1):

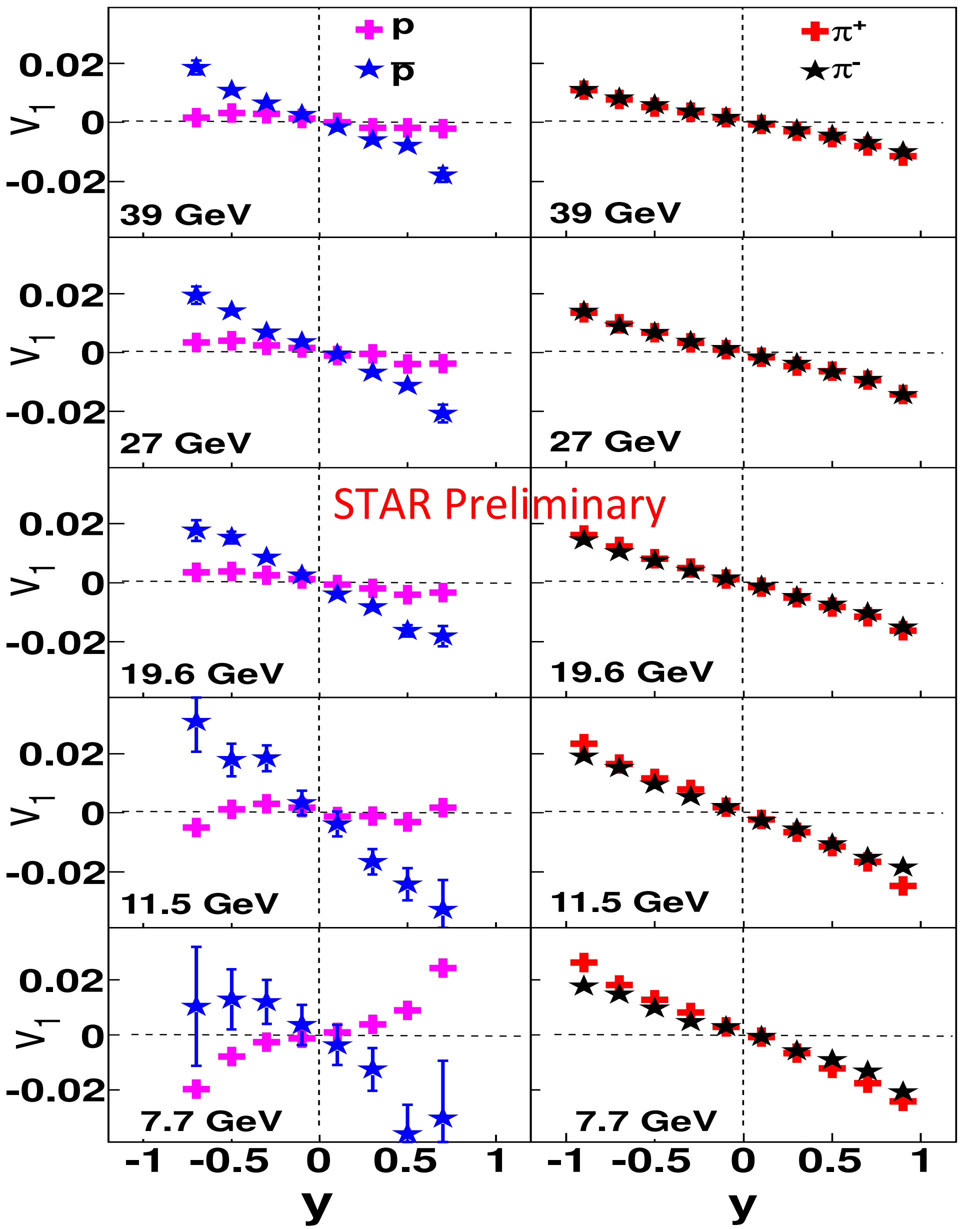
SQM2011: Acta Physica Polonica B Vol. 5, No. 2, 2012, page 439

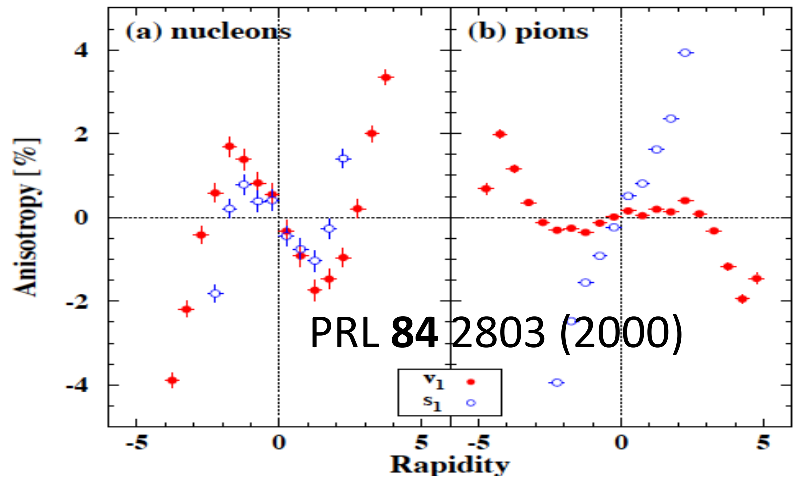


- Approximate scaling is observed for peripheral(30-60% centrality) collisions as a function of η/y_{beam} and $\eta - y_{beam}$
- Limiting fragmentation hypothesis.

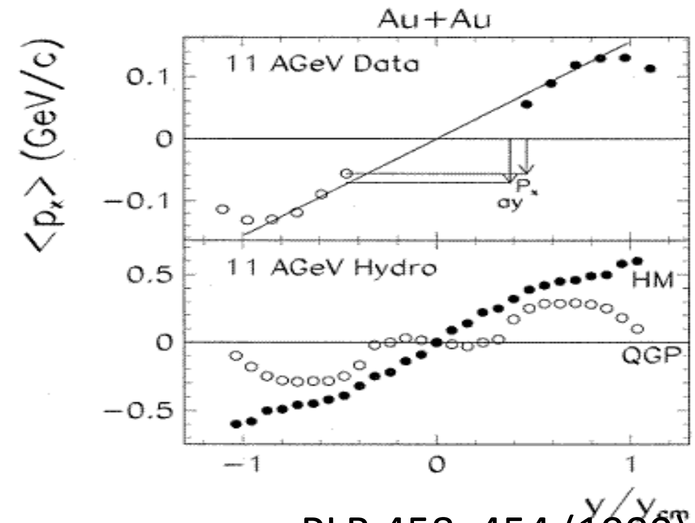
Directed flow: protons and pions

STAR: QM2012





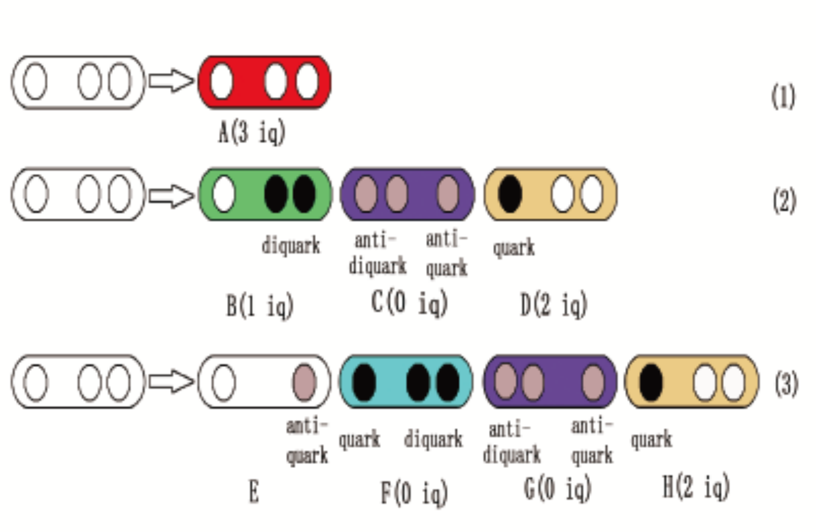
PRL **84** 2803 (2000)

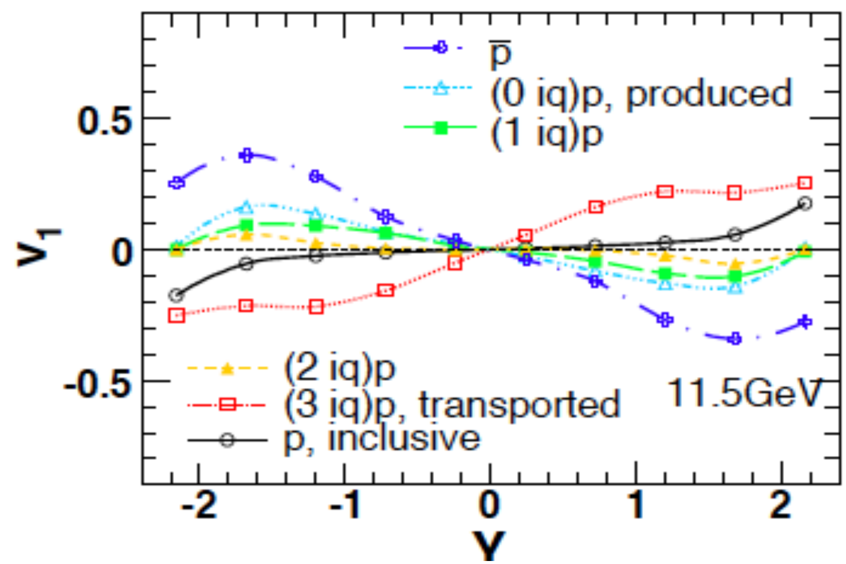


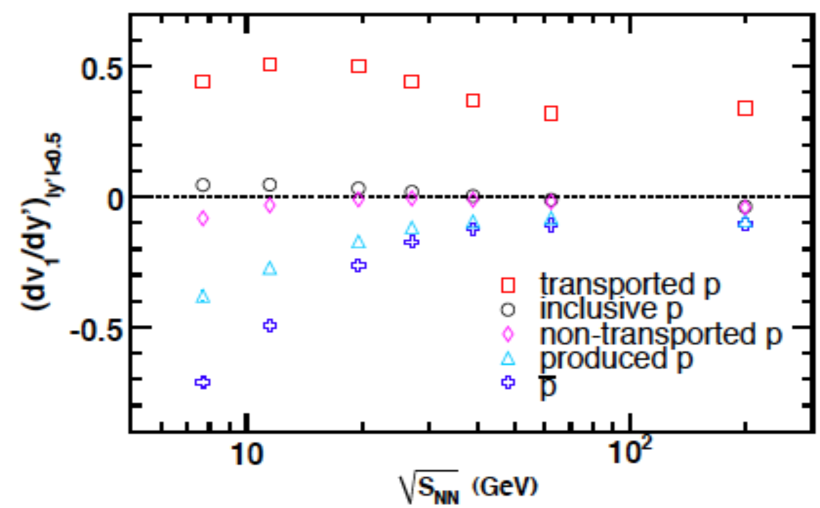
PLB 458, 454 (1999)

Above 11.5 GeV data favours anti-flow picture(3rd flow component)

Transported and produced protons





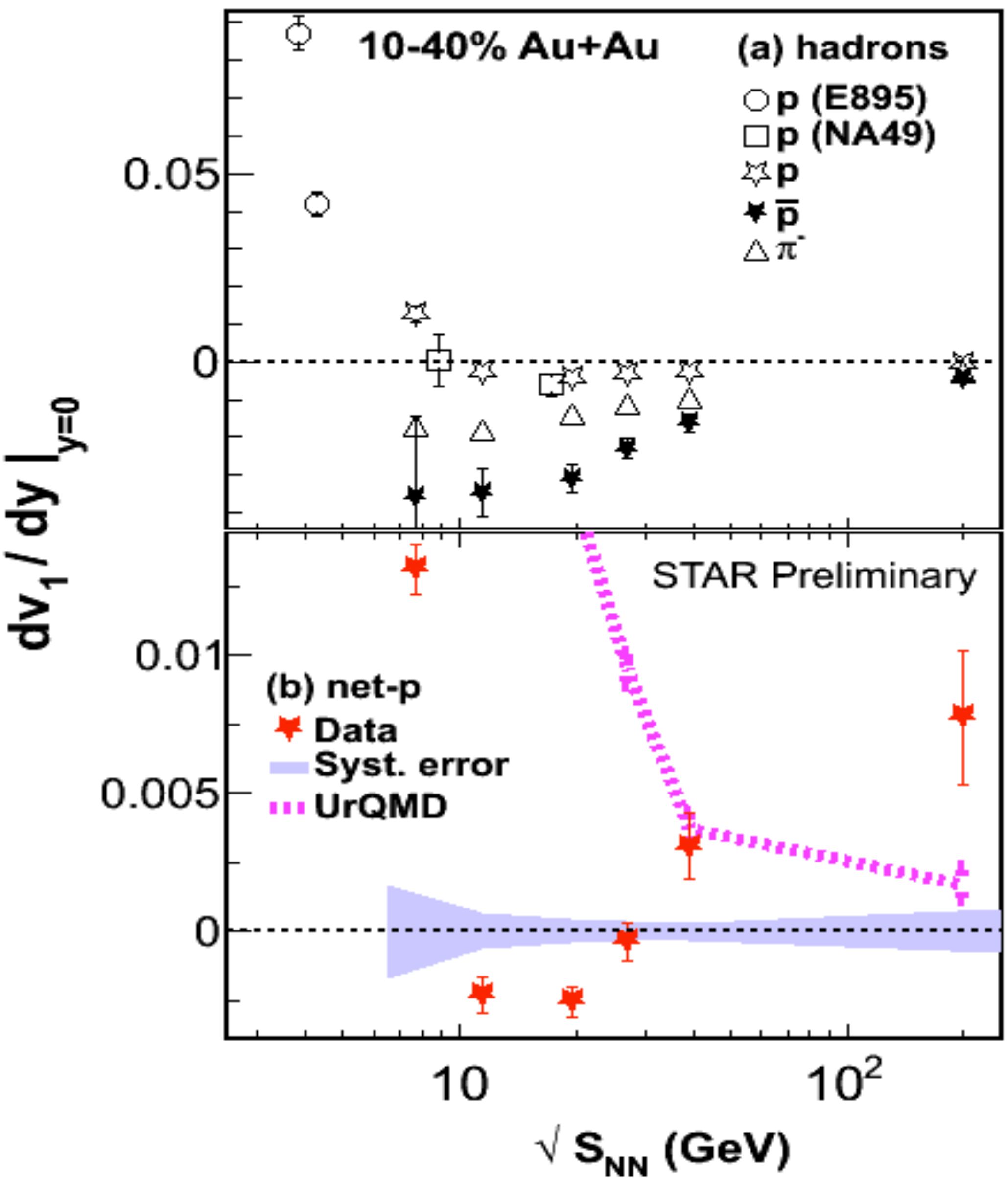


The inclusive protons v_1 is convolution of produced protons and transported protons

Y. Guo, F. Liu, A.Tang, Phys. Rev. C 86, 044901 (2012)

Directed flow: protons and pions

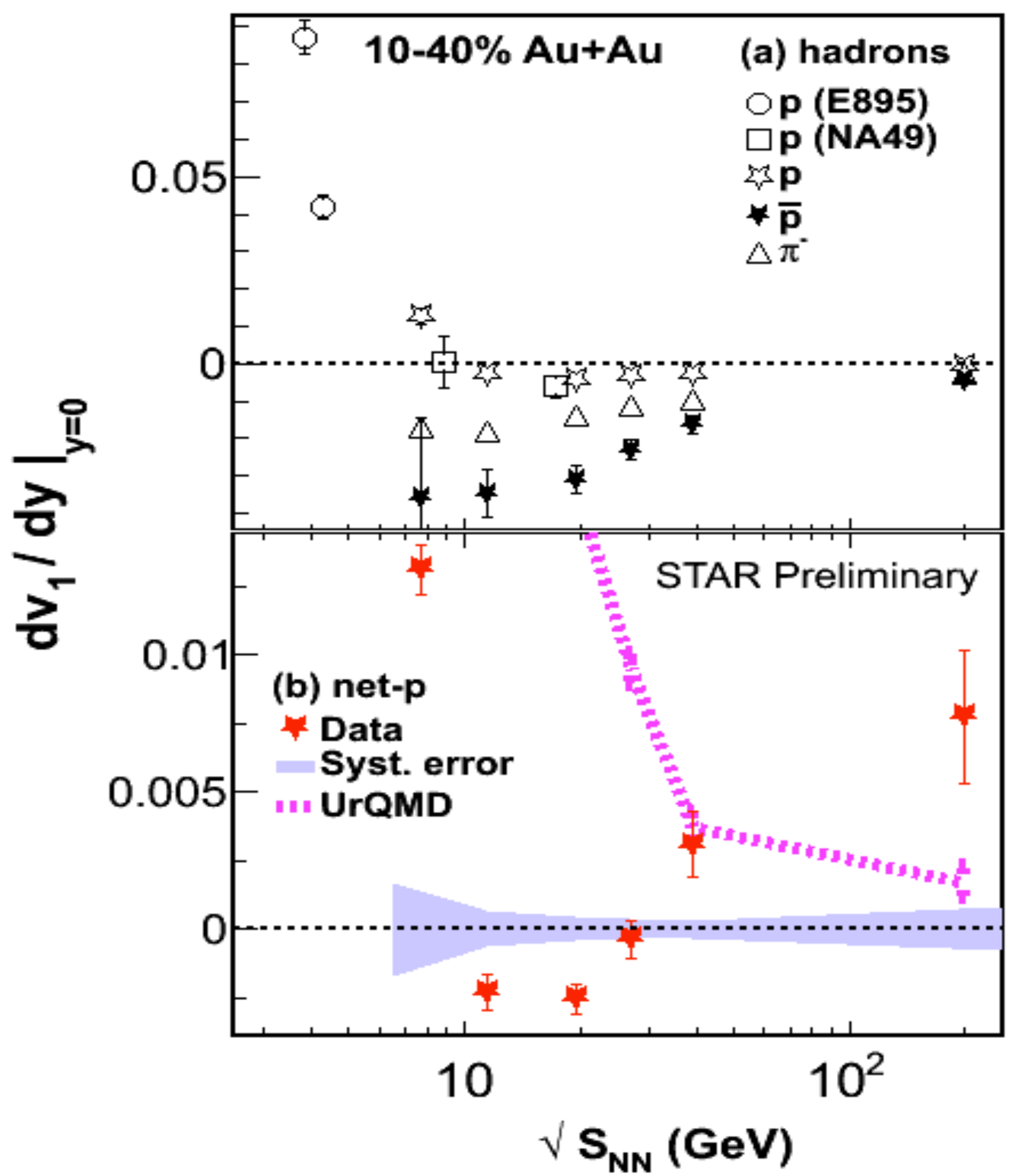
STAR: QM2012



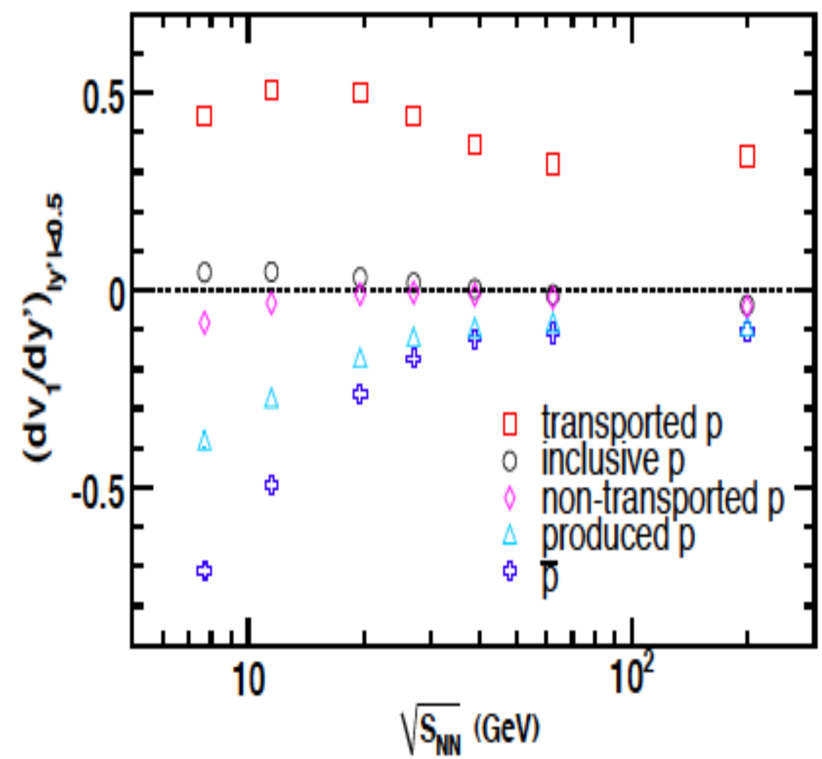
- Proton directed flow "collapses". at 11.5 and higher beam energies
- Antiproton v_1 has the same sign of that of pions - the collapse of proton v_1 is not a mass effect.
- Net-proton (transported protons) show double sign change

Directed flow of Protons: transoported and produced

STAR: QM2012

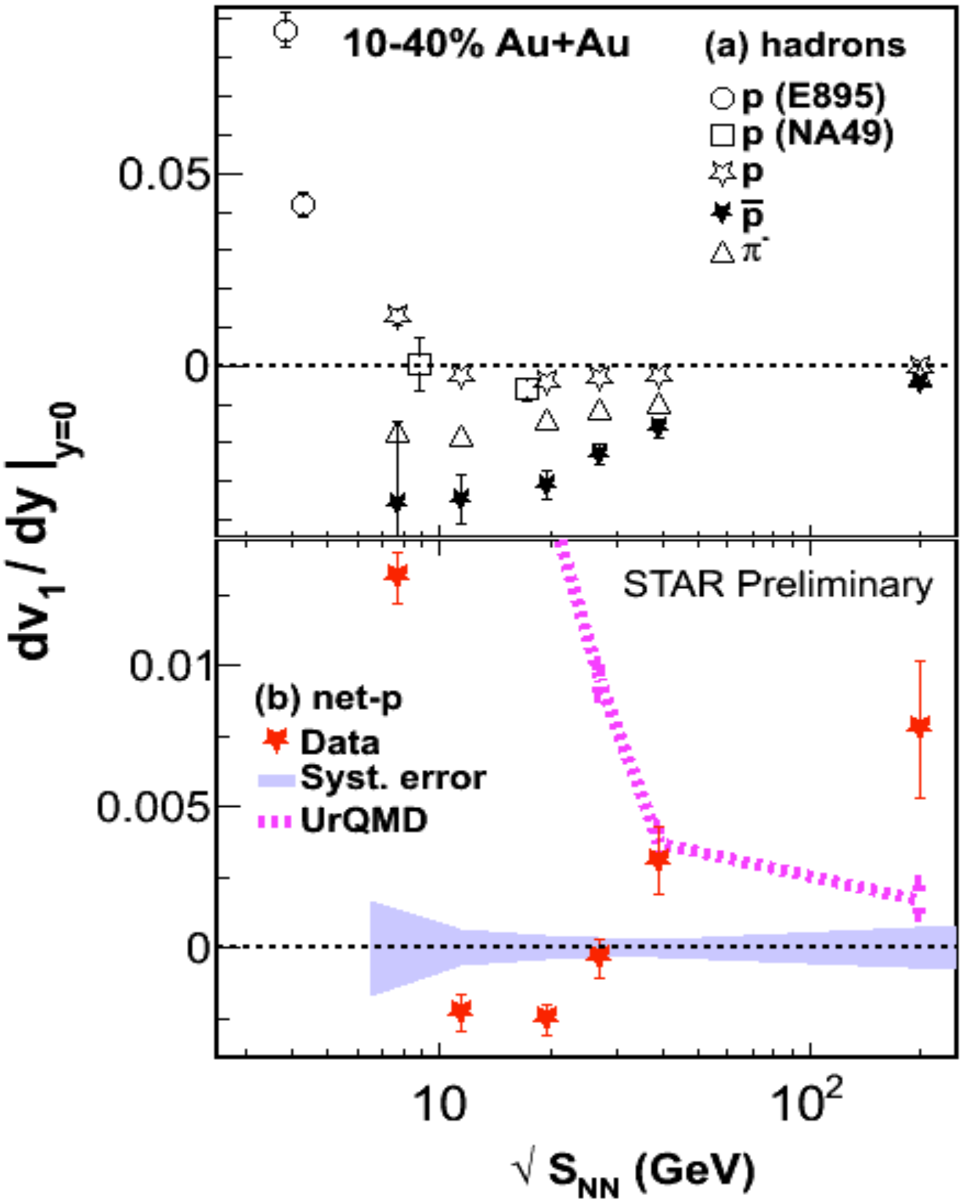


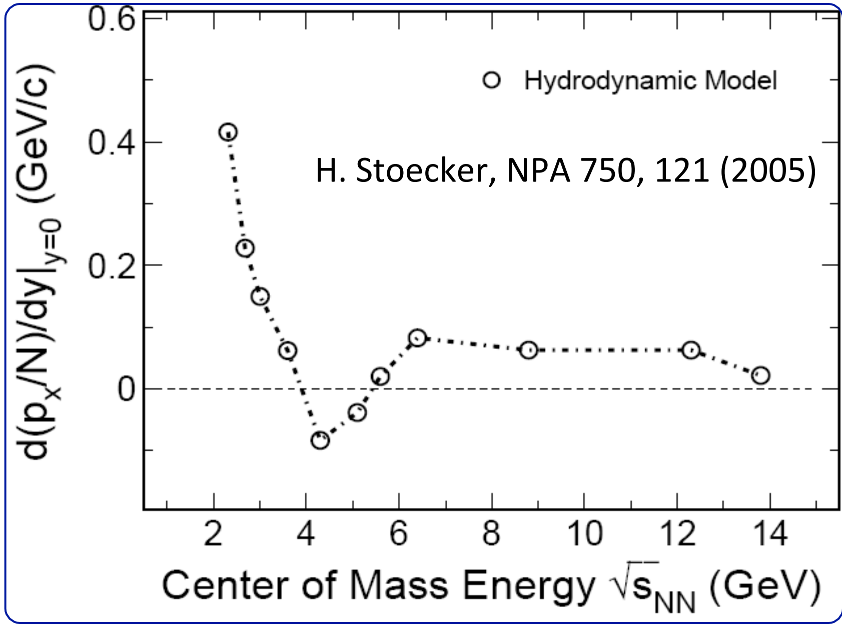
PRC 86, 044901 (2012)



Data differs strongly from a hadronic transport calculation.

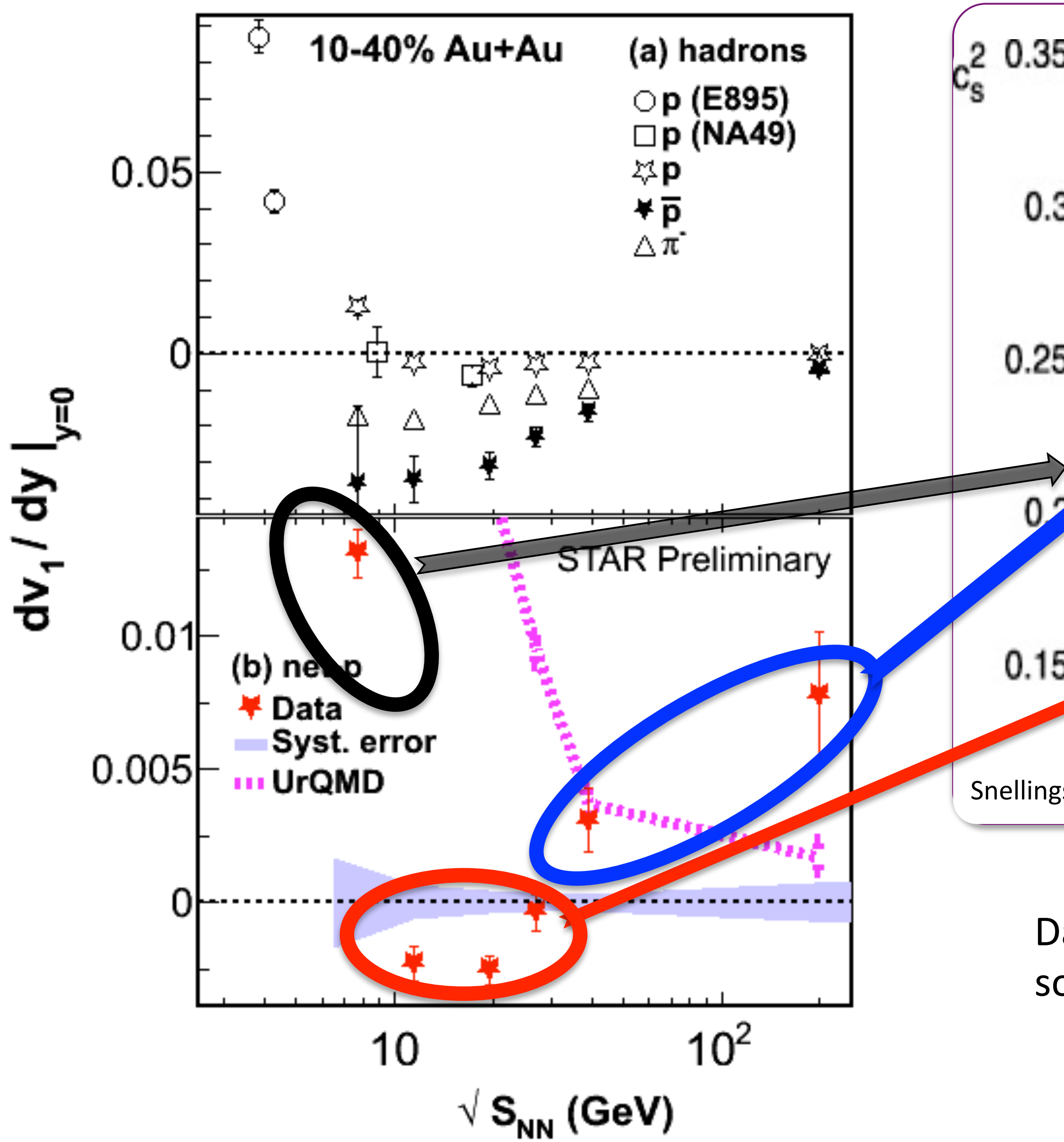
Directed flow of transoported protons

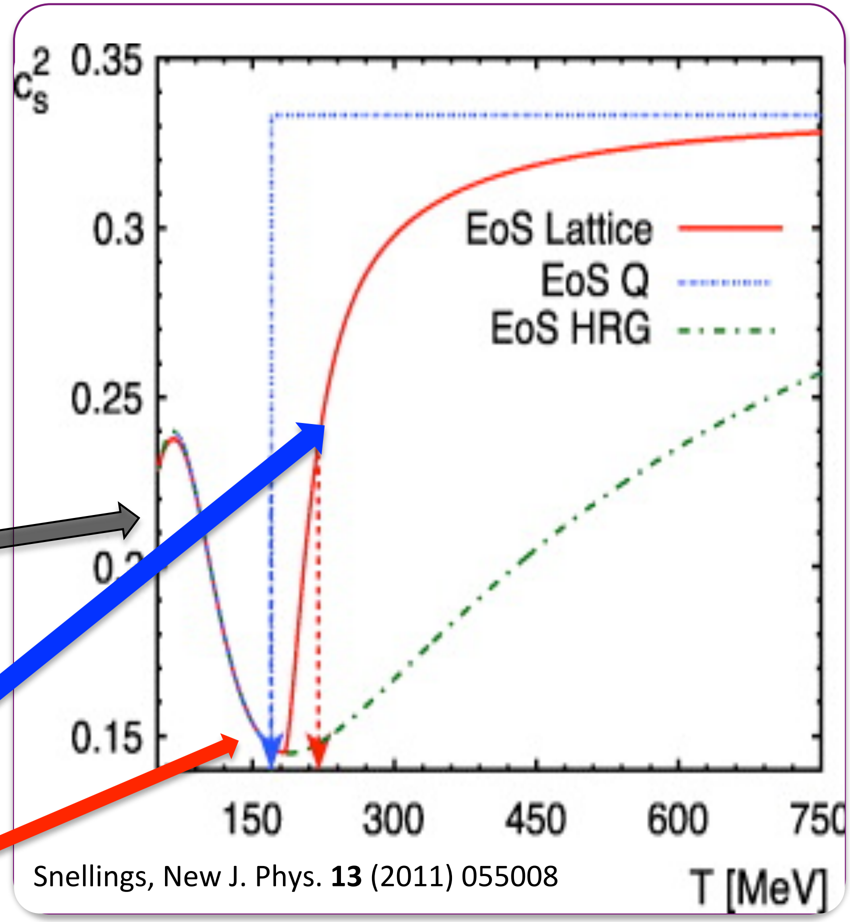




Data qualitatively resembles predictions of a hydrodynamic model with a first-order phase transition

Directed flow of transoported and produced protons

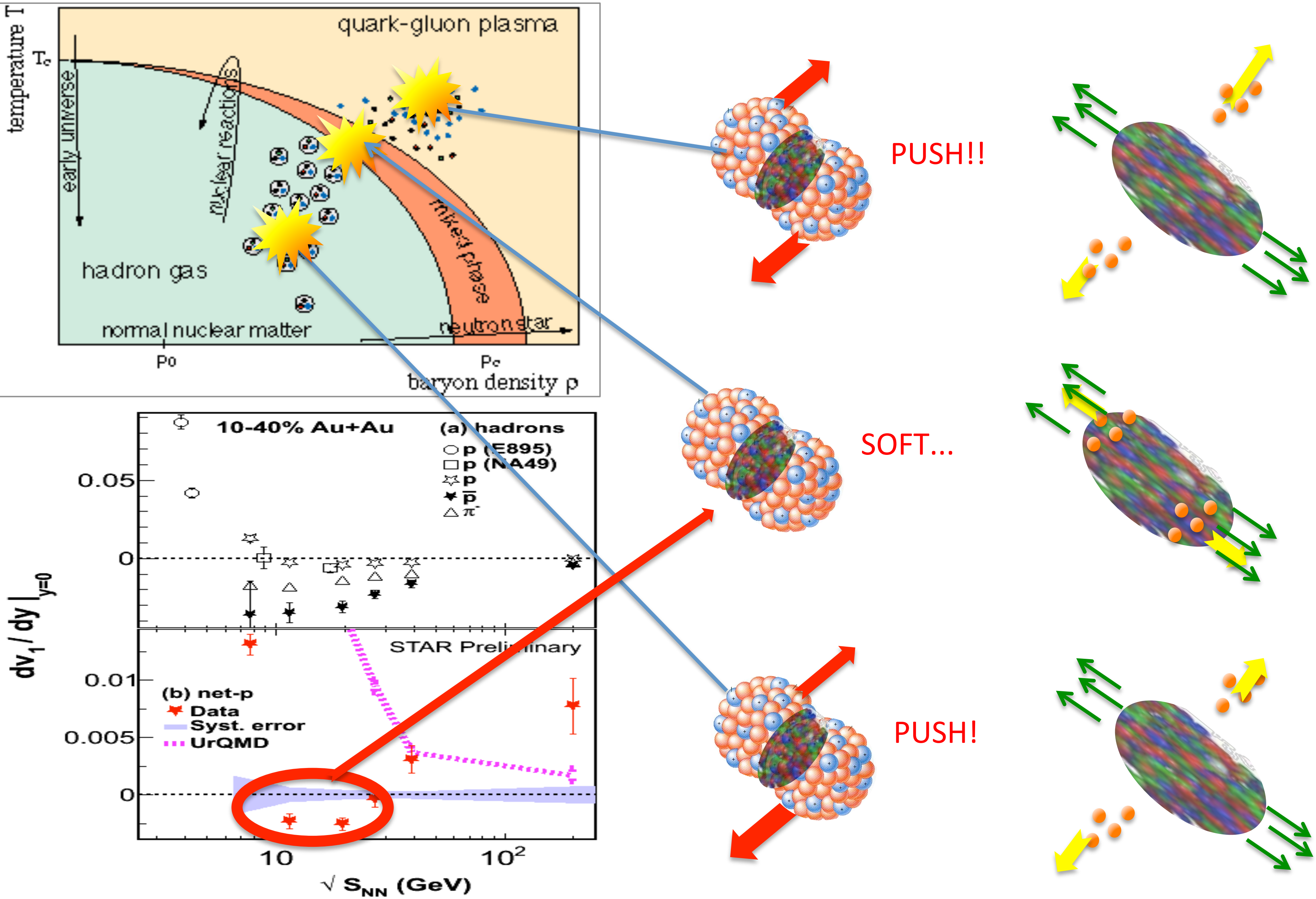




Snellings, New J. Phys. **13** (2011) 055008

Data may have pointing towards the soft point

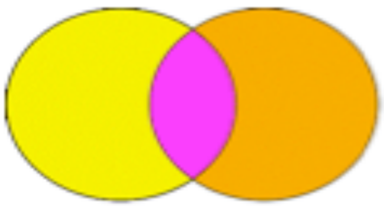
Directed flow of transoported protons

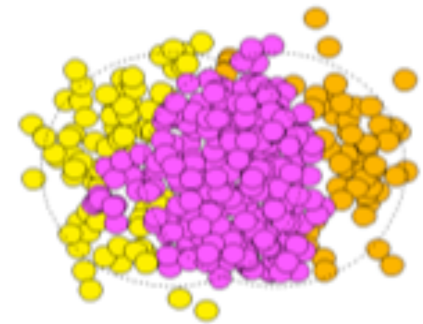


Rapidity-even Directed Flow from initial state fluctuations

Directed flow and Initial state fluctuations

Recent understanding points to the 'lumpy' initial state.





Odd harmonics ≠ 0

Elliptic flow(v_2)

$v_n(v_1, v_2, v_3, v_4, v_5, --)$

- Fluctuations imply odd terms aren't necessarily zero.
- Provide valuable information to study the evolution of the system.

Takahashi et al, PRL 103, 242301 (2009), Hama et al, arXiv:0911.0811, P. Sorensen, J. Phys. G 37, 094011 (2010) ,B. Alver et al, PRC 81, 054905 (2010)

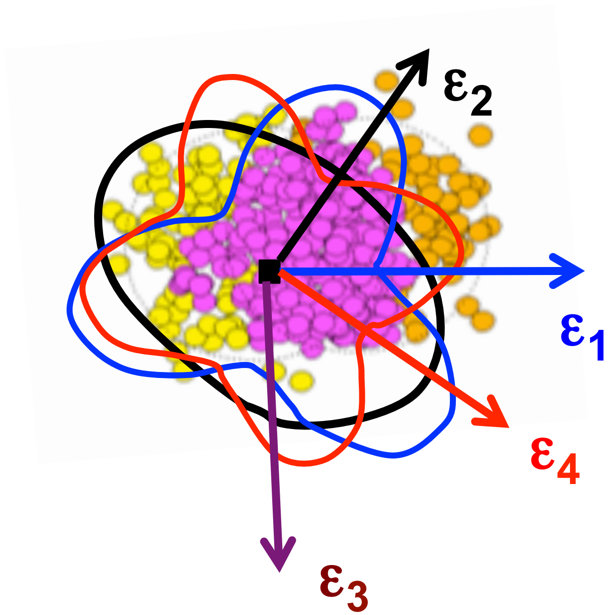
Directed flow and Initial state fluctuations

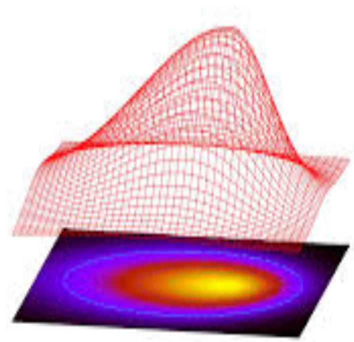
Initial geometry fluctuations

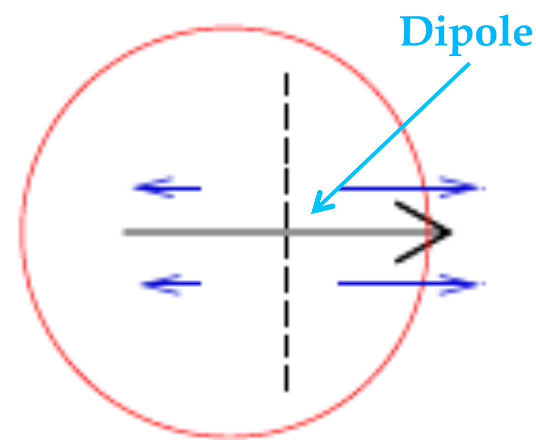
Miller et al nucl-ex/0701025

Dipole asymmetry:

D. Teany et. all PRC 83, 064904(2011)



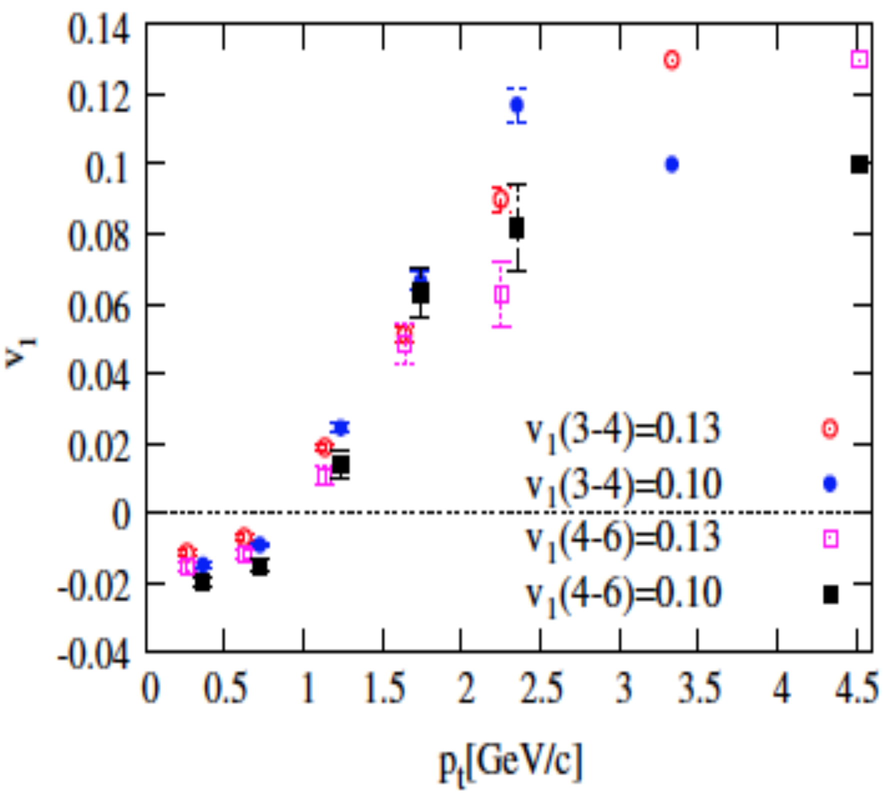


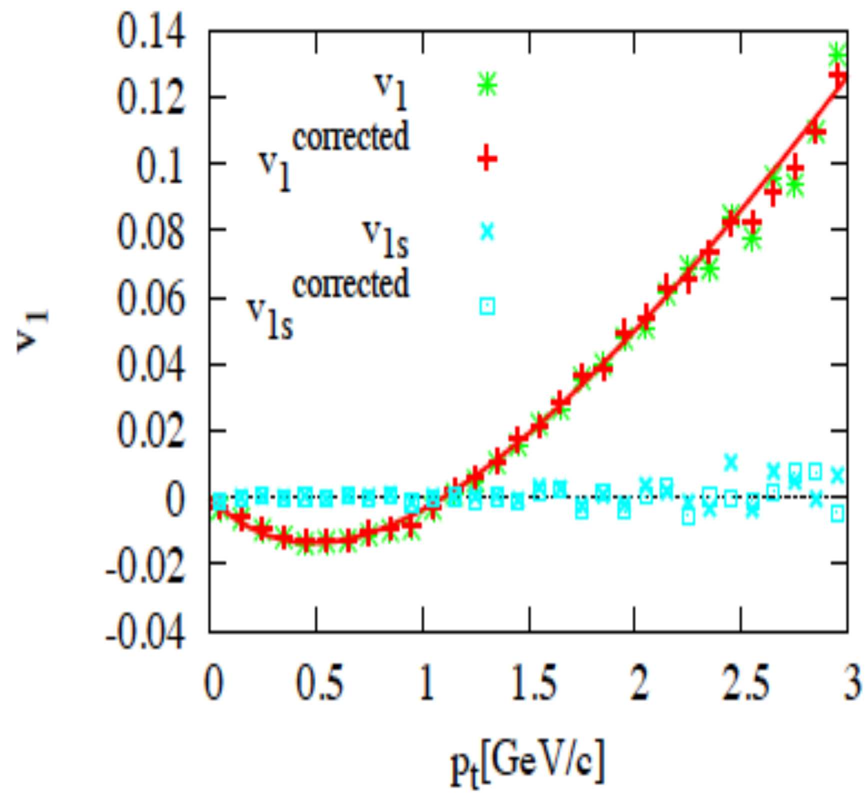


$$\varepsilon_1 e^{i\phi_1} = -\frac{\langle r^3 e^{i\phi} \rangle}{\langle r^3 \rangle}$$

ε_1=> magnitude of dipole asymmetry, ϕ_1=>steepest direction for a profile, (r,ϕ)=>polar coordinate system

Directed flow and Initial state fluctuations

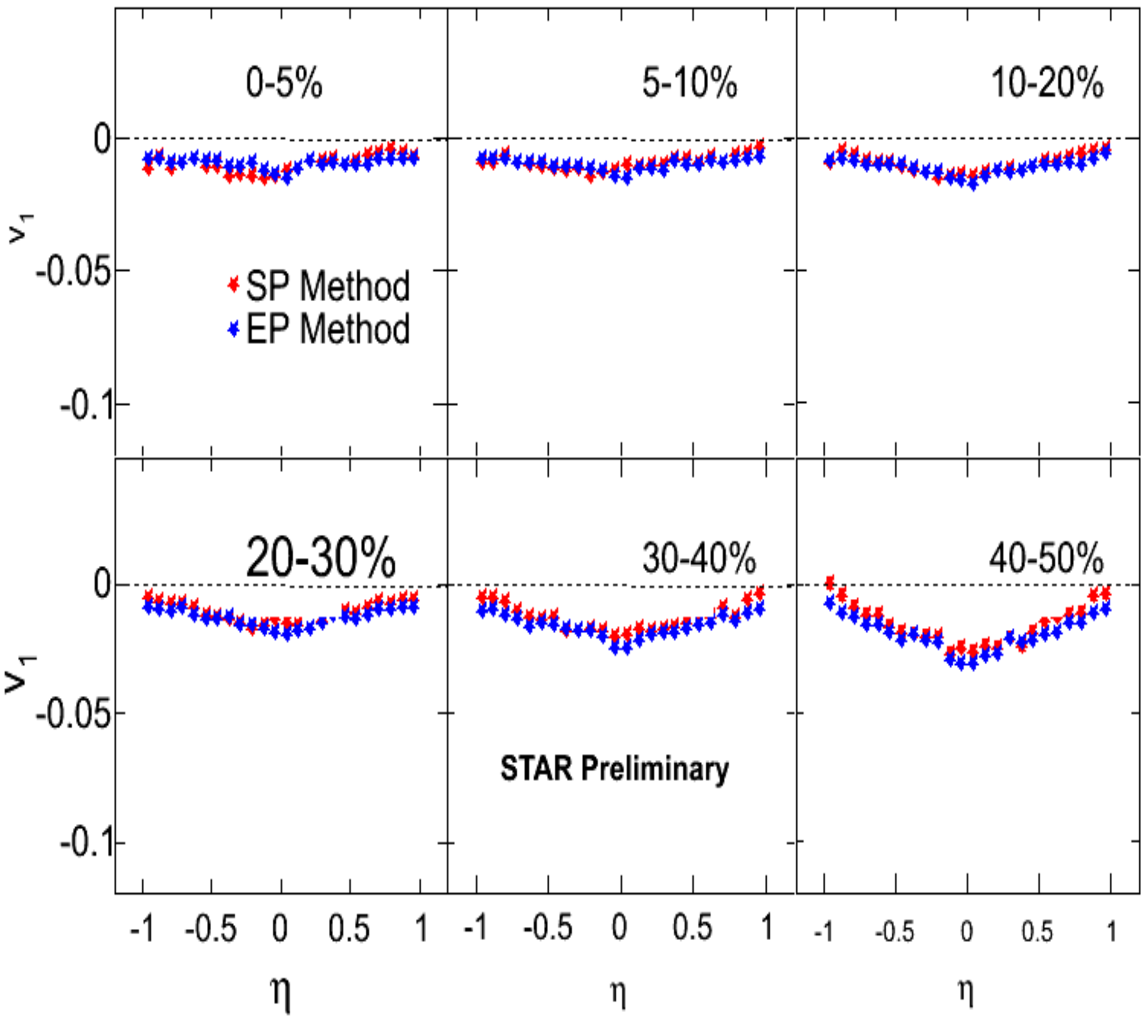




- M. Luzum et. all (PRL 106, 102301 (2011)) extracted possible v_1 signal from STAR correlation data[H. Agakishiev et al., arXiv:1010.0690]
- Ideal hydrodynamic model prediction by F. G. Gardim et. all(PRC 83, 064901 (2011)) for 0-40% central collisions

Directed flow and Initial state fluctuations

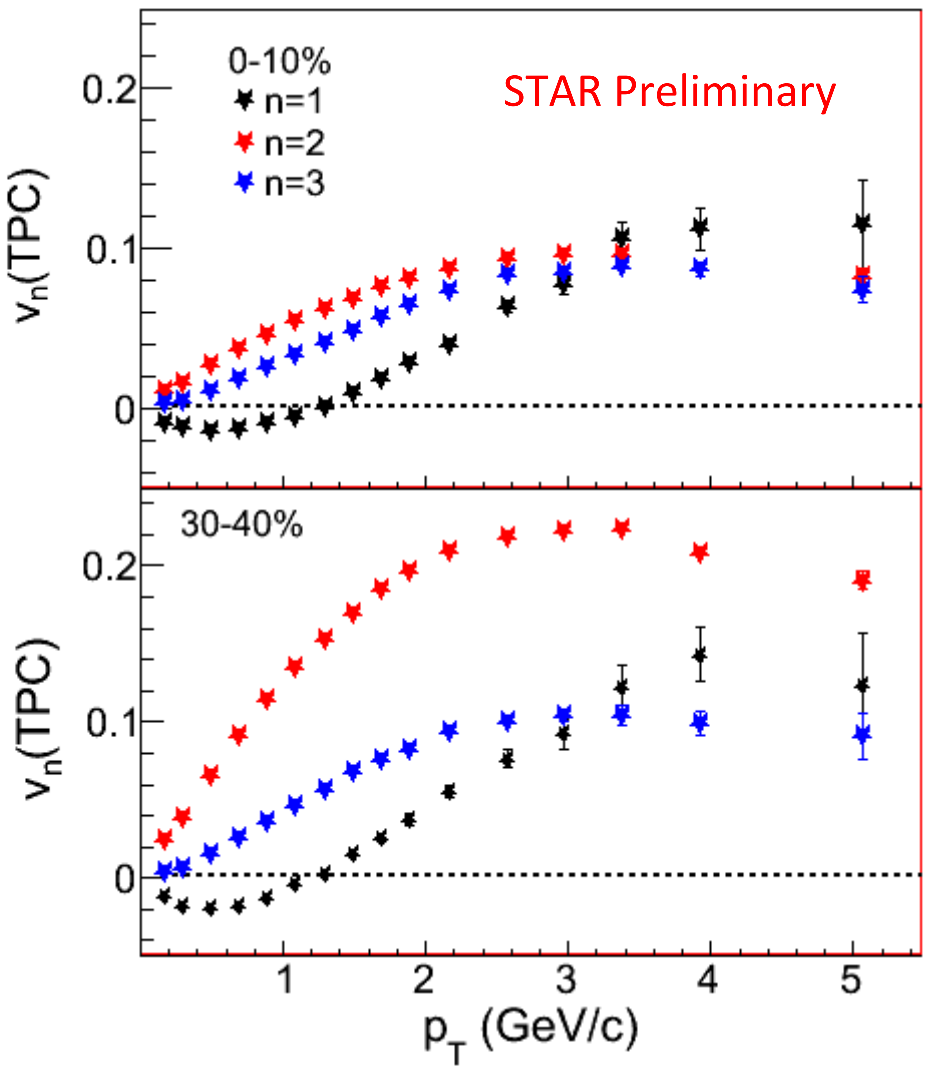
STAR Collaboration, HQ 2012



- Symmetric with respect to pseudorapidity (PRL 106,102301(2011)
- Some pseudorapidity dependence at peripheral collisions.
  Viscous effect(??)
  Non flow (??)

Directed flow and Initial state fluctuations

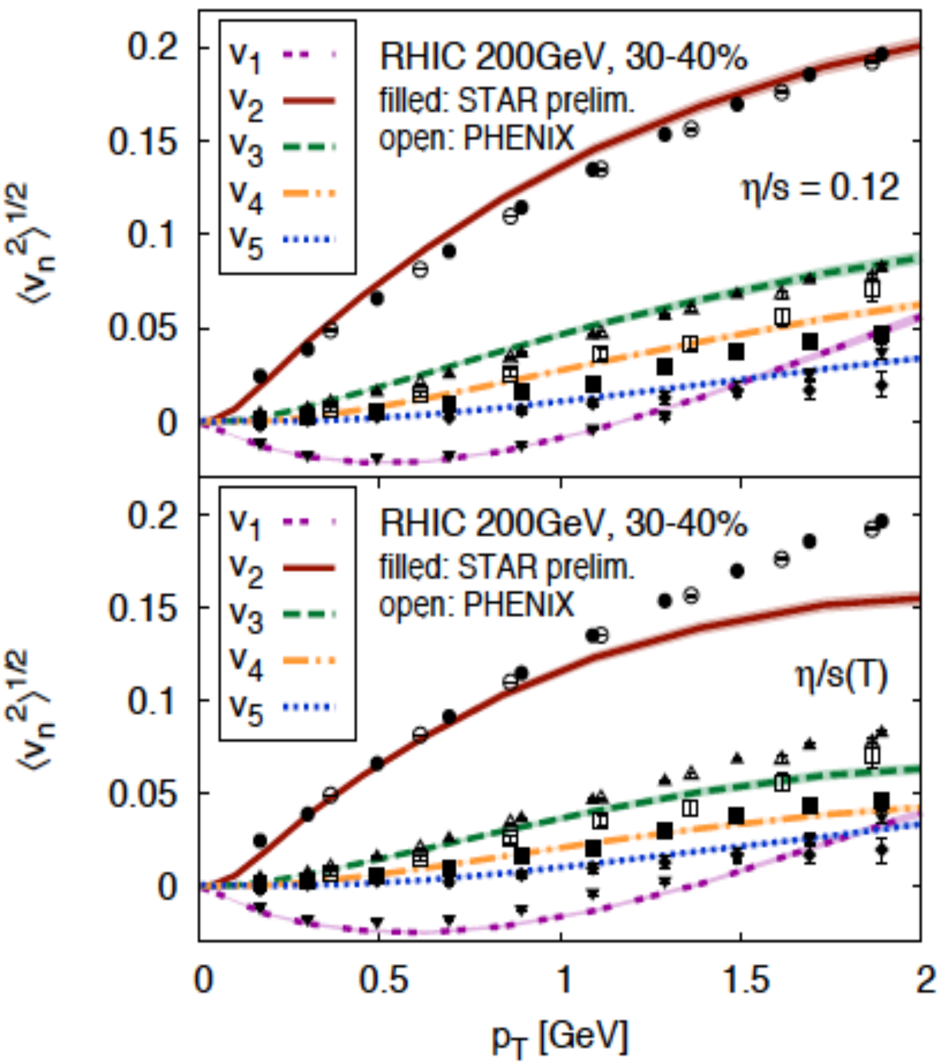
STAR Collaboration, HQ 2012



- At intermediate p_T, its magnitude is comparable to v_2 and v_3 in central collisions (0-10%), even exceeds v_3 at mid central collisions (30-40%).
- Increases up to p_T ~ 4GeV/c (Similar to ATLAS result) PRC 86, 014907 (2012)

Directed flow and Initial state fluctuations

Phys. Rev. Lett. 110, 012302,(2013).

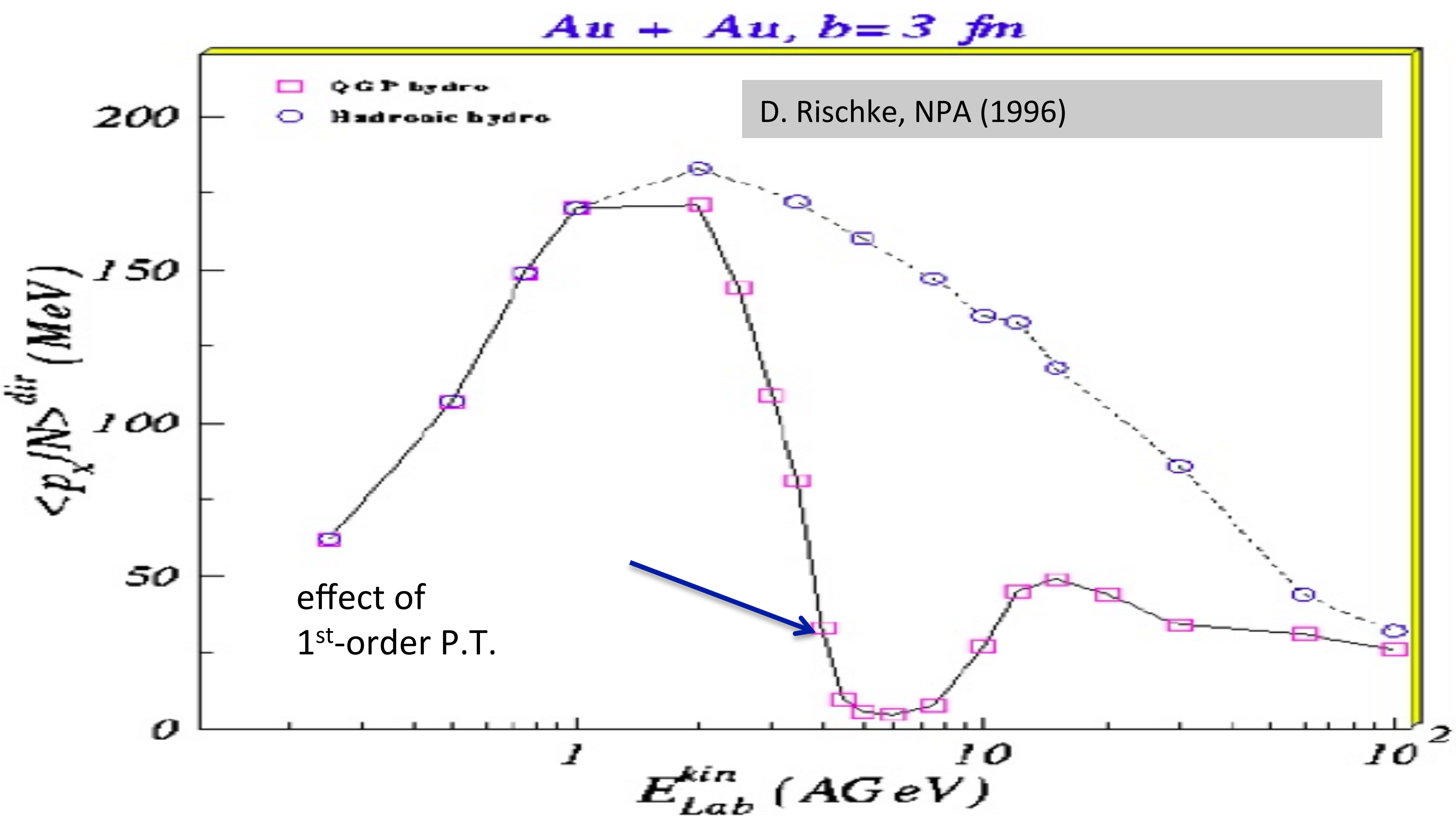


Hydrodynamic model with event by event fluctuations and low viscosity setting describe the all harmonics well

Summary

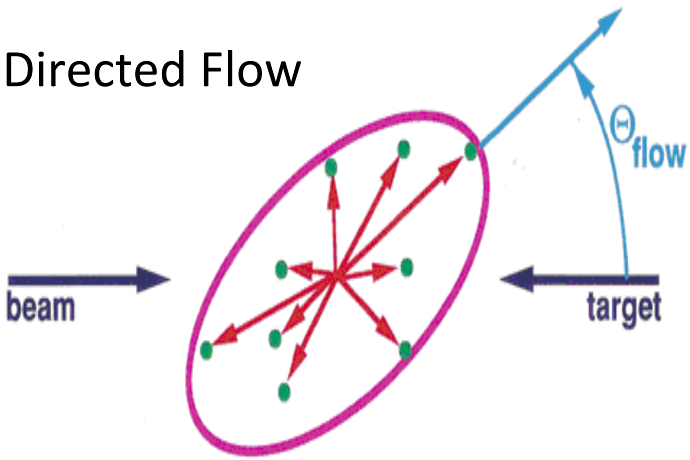
- Anisotropic flow measurements are important tools to understand the collisions dynamics in heavy ion collisions.
- First-order azimuthal anisotropy measures respond to anisotropy imprinted at interpenetration
- Proton directed flow "collapses" at 11.5 and higher beam energies.
- Net-proton(transported protons) show double sign change. Data differs strongly from a hadronic transport calculation and qualitatively resembles predictions of a hydrodynamic model with a first-order phase transition
- Directed flow measurements at BES energies have provided some important/interesting hints to further explore the QCD Phase Diagram.

Extra Slides

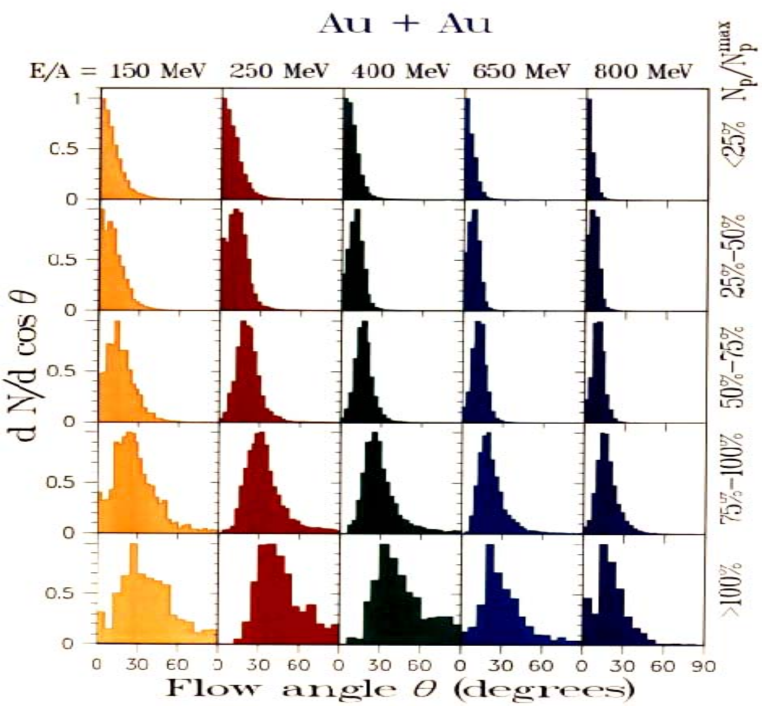


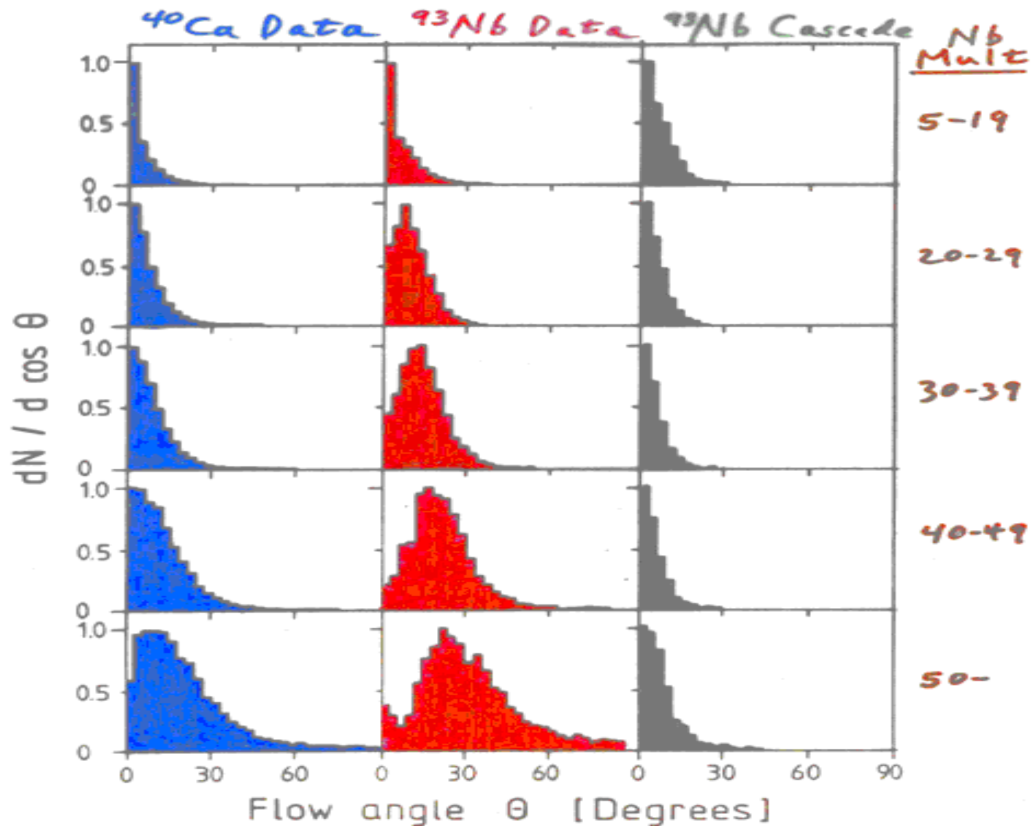
Heavy ion Collisions: Directed flow

Directed Flow



"The only true signature of collective flow is a clear maximum of dN/d cosθ away from θ = 0"
M. Gyulassy, K.A. Frankel, and H. Stocker, Phys. Lett. 110B, 185 (1982)





Plastic Ball, Gustafsson et al., PRL 52, 1590 (1984)
Plastic Ball, H.G. Ritter et al., Nucl. Phys. A447, 3c (1985)