Evolution of anisotropic flow of produced particles from Au+Au collisions at $\sqrt{s_{NN}}$ = 4.5 - 200 GeV in a hybrid models

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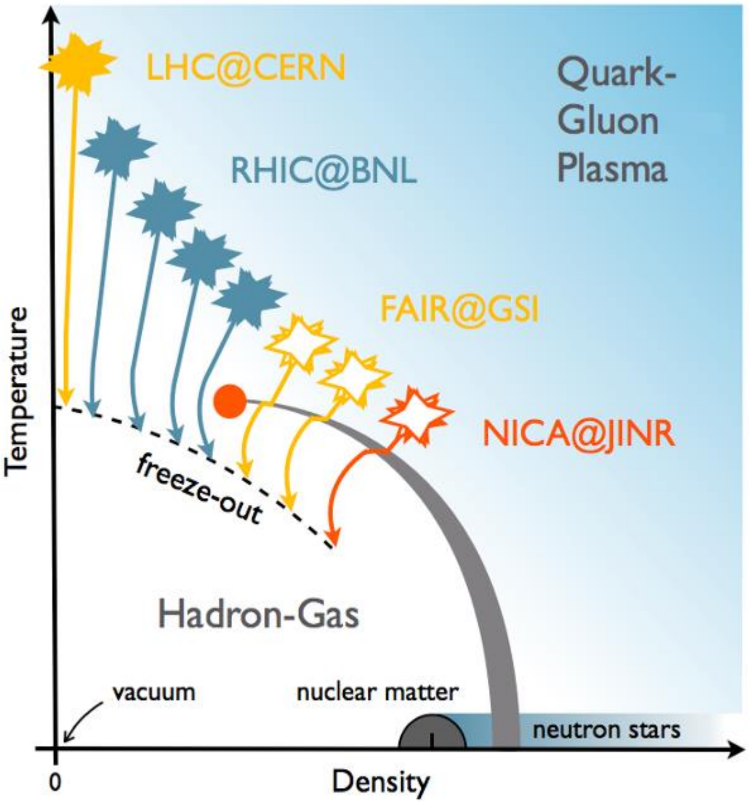
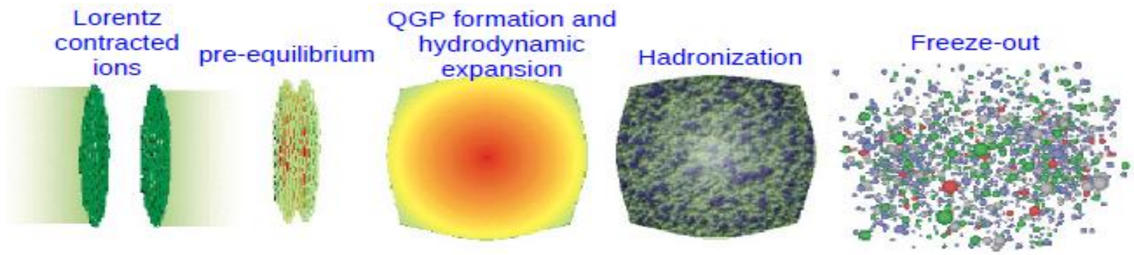
OUTLINE

1. Why measure anisotropic flow?
2. Anisotropic flow (V_n) and sQGP at RHIC/LHC
3. Elliptic flow results from Beam Energy Scan (RHIC) and comparison with hybrid models
4. Outlook for flow measurements at NICA

Phase Diagram of the Strongly-Interacting Matter



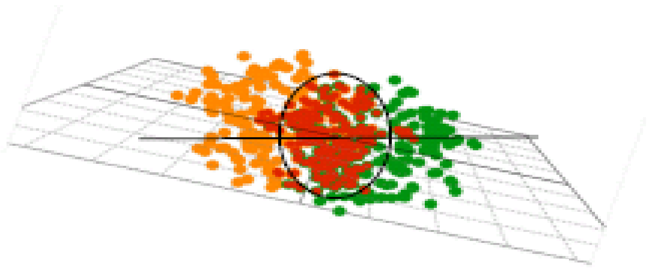
Top RHIC/LHC: validation of the cross over transition leading to the sQGP



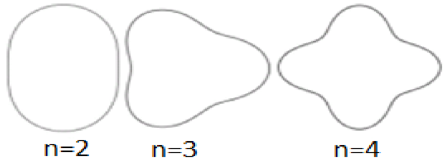
- *Top RHIC energy /LHC - access to high T and small μ_B*
- *RHIC-BES/SPS/NICA/FAIR - access to different systems and a broad domain of the (μ_B,T)-plane*

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

Anisotropic Collective Flow at RHIC/LHC

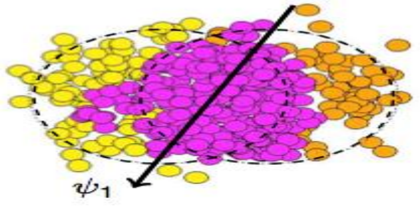


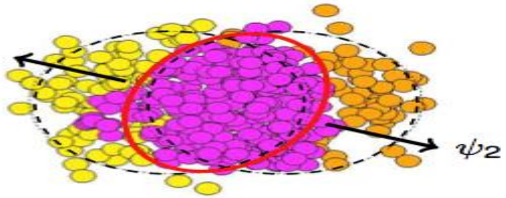
$$\epsilon_n = \sqrt{\frac{\langle r^n \cos n\phi \rangle + \langle r^n \sin n\phi \rangle}{\langle r^n \rangle}}$$



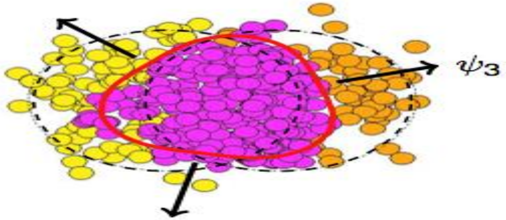
$$\frac{dN}{d\phi} \propto \left(1 + 2\sum_{n=1} v_n \cos\left[n\left(\phi - \Psi_n\right)\right]\right)$$

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



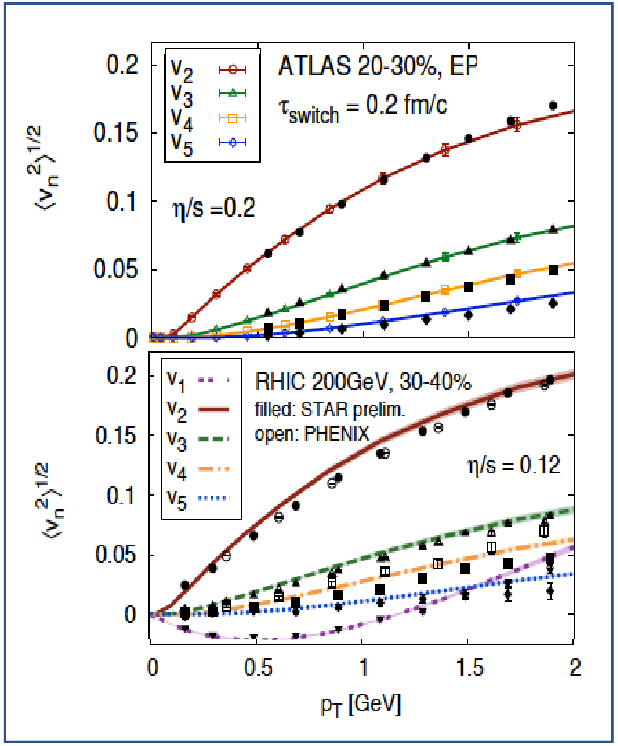


v_2 - elliptic flow

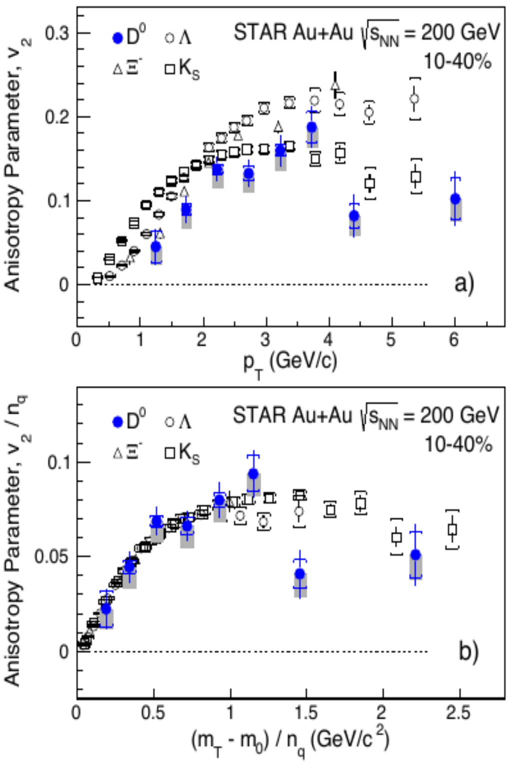


v_3 - triangular flow

Anisotropic Collective Flow at top RHIC / LHC



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



STAR PRL118 (2017) 212301

v_n (p_T, centrality) - sensitive to the early stages of collision.
Important constraint for transport properties: EOS, η/s, ζ/s, etc.

v_n of identified hadrons:

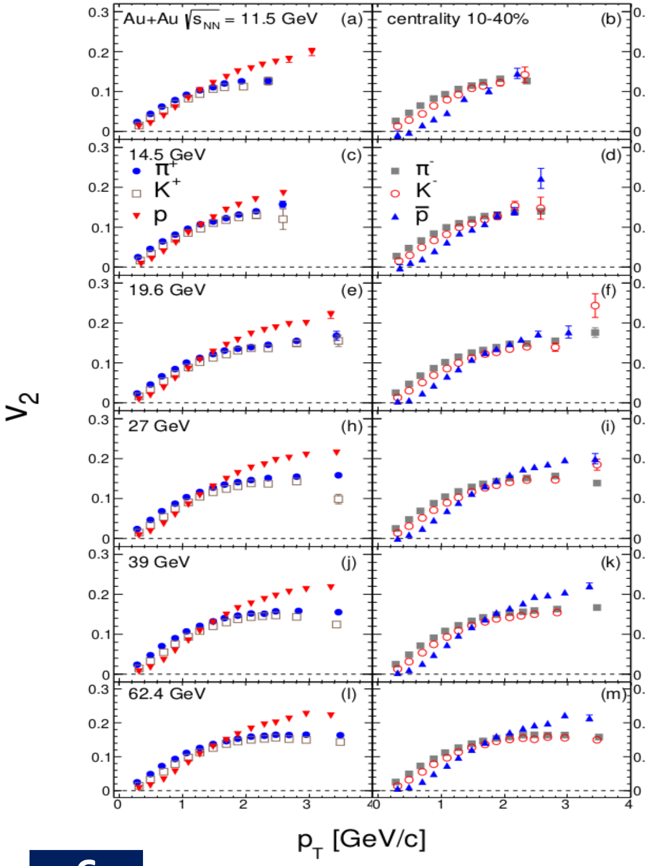
Mass ordering at p_T < 2 GeV/c (hydrodynamic flow, hadron rescattering)

Baryon/meson grouping at p_T > 2 GeV/c (recombination/coalescence), Number of constituent quark (NCQ) scaling

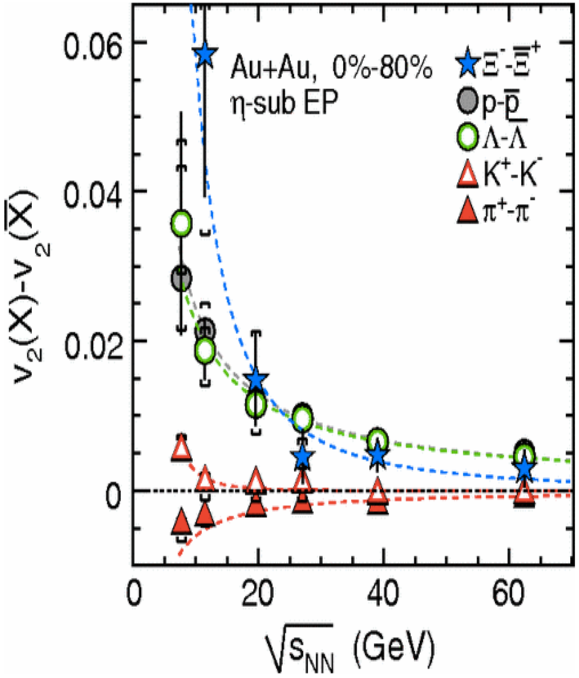
No difference between particles and antiparticles

Beam-Energy Dependence of Elliptic Flow (v_2)

STAR: Phys. Rev. C 93 (2016) 14907



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



- Small change in v_2 (p_T) for inclusive and identified charged hadrons (pions, kaons and(anti)protons) as the $\sqrt{s_{NN}}$ changes by a factor ~25 (from 7.7 GeV to 200 GeV) .
- Substantial particle-antiparticle split at lower energies

Goal of this work:

1) Perform simulations with hybrid models (vHLLE+UrQMD and AMPT), analyse them as in the real experiment and make comparison with RHIC BES published measurements of v_2.

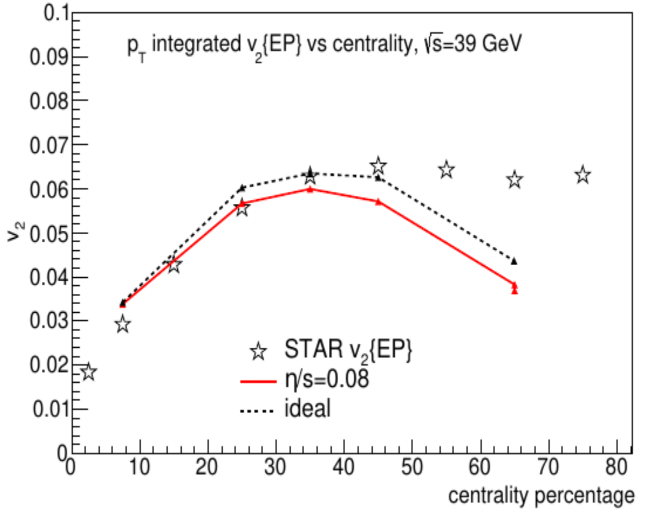
2) Make projections for measurements at NICA energies (**$\sqrt{s_{NN}}$ = 4 – 11 GeV**)

Hybrid models for anisotropic flow at RHIC/LHC

1) UrQMD + 3D viscous hydro model vHLLE + UrQMD

Iurii Karpenko, Comput. Phys. Commun. 185 (2014), 3016
https://github.com/yukarpenko/vhlle
Parameters: from Iu. A. Karpenko, P. Huovinen, H. Petersen, M. Bleicher, Phys. Rev. C91 (2015) no.6, 064901 – good description of STAR BES results for v_2 of inclusive charged hadrons (7.7 – 62.4 GeV)

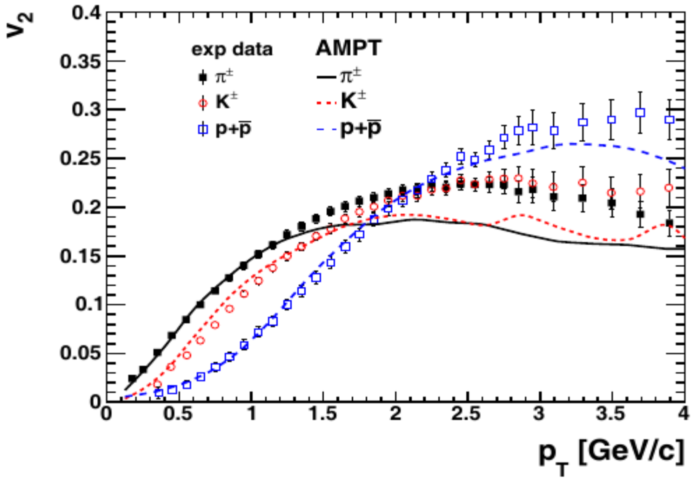
Initial conditions: model UrQMD
QGP phase: 3D viscous hydro (vHLLE) with crossover EOS (XPT)
Hadronic phase: model UrQMD



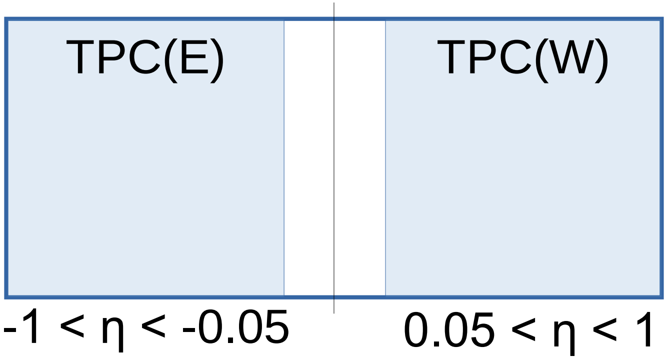
2) A Multi-Phase Transport model (AMPT) for high-energy nuclear collisions. *The main source codes: Zi-Wei Lin (http://myweb.ecu.edu/linz/ampt/v1.26t9b/v2.26t9b)*

***Initial conditions:* model HIJING**
***QGP phase:* Zhang's parton cascade for modeling partonic scatterings**
***Hadronic phase:* model ART**

Z.W. Lin, C. M. Ko, B.A. Li, B. Zhang and S. Pal: Physical Review C 72, 064901 (2005).



Analysis method: Event plane method (η-sub)



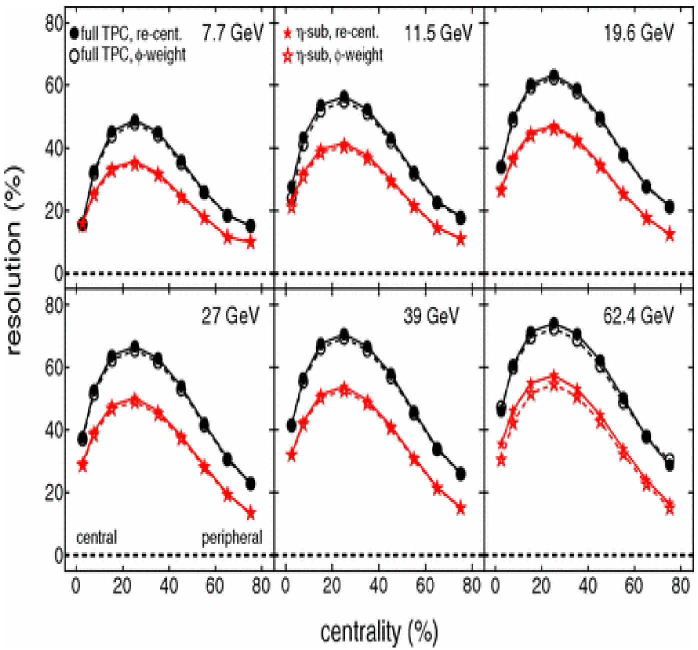
TPC (E) $half(\eta < 0) \rightarrow \eta_-$

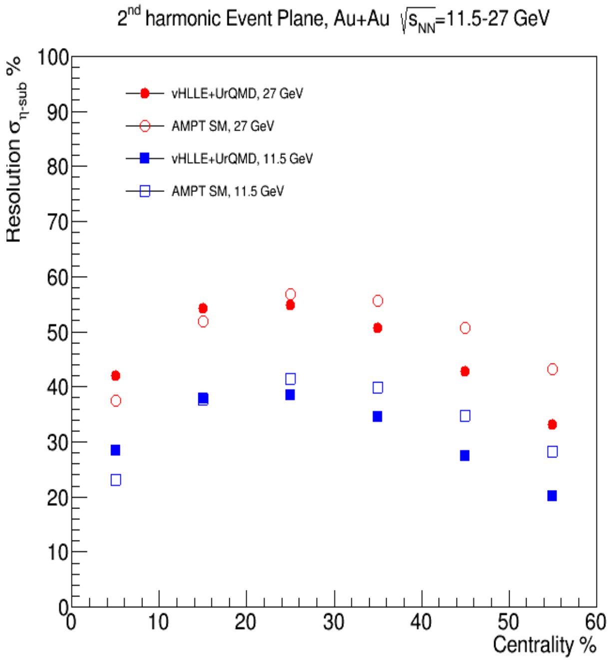
$TPC\ (W)\ half(\eta > 0) \rightarrow \eta_+$

$$v_n = \frac{\langle \cos[n(\varphi_{\eta\pm} - \Psi_{n,\eta\mp})] \rangle}{\sqrt{\langle \cos[n(\Psi_{n,\eta+} - \Psi_{n,\eta-})] \rangle}}$$

resolution

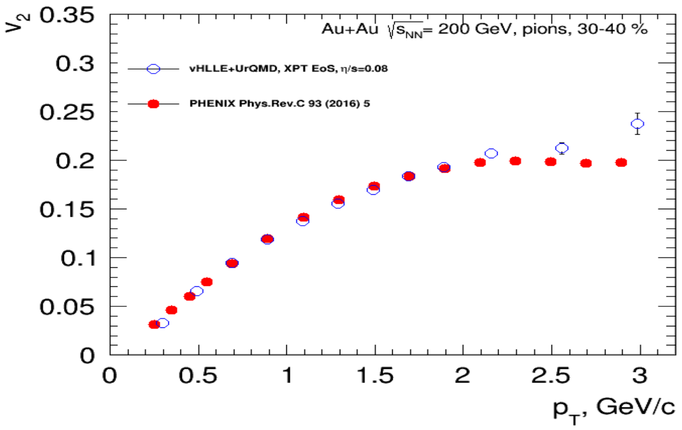
STAR Phys. Rev. C 88 (2013) 14902

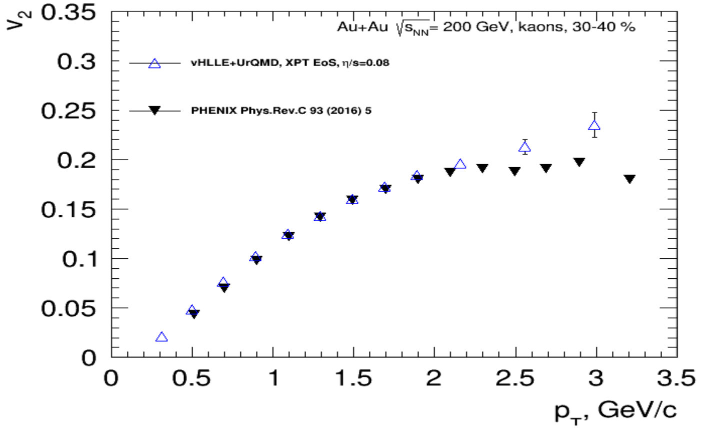


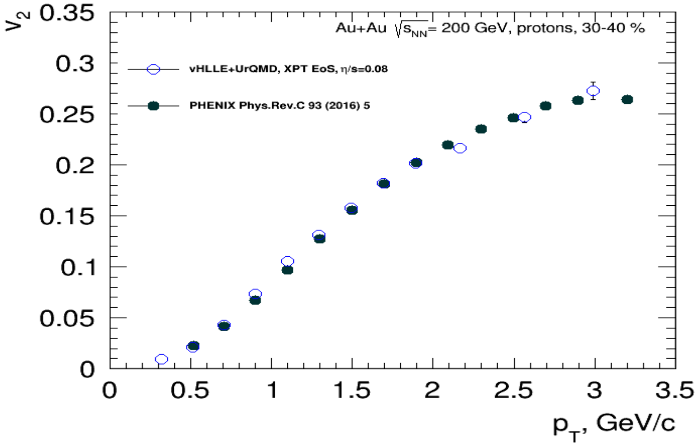


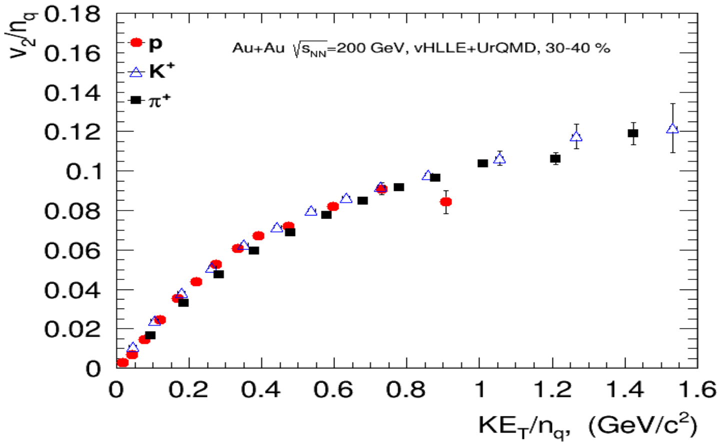
The resulting values for event plane resolution for simulated events from hybrid models: vHLLE+UrQMD and AMPT are close to STAR experimental data.

vHLLE+UrQMD: Elliptic flow at top RHIC energy : $\sqrt{s_{NN}}$ = 200 GeV



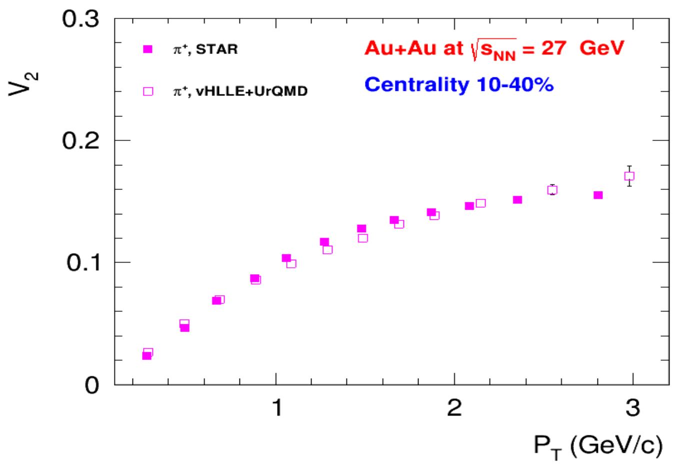


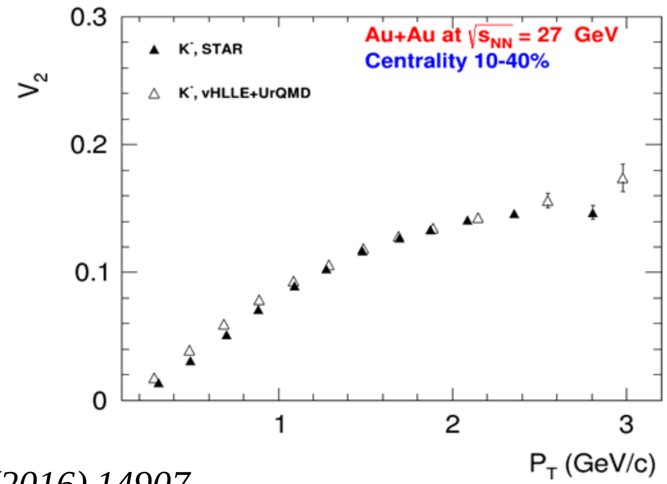




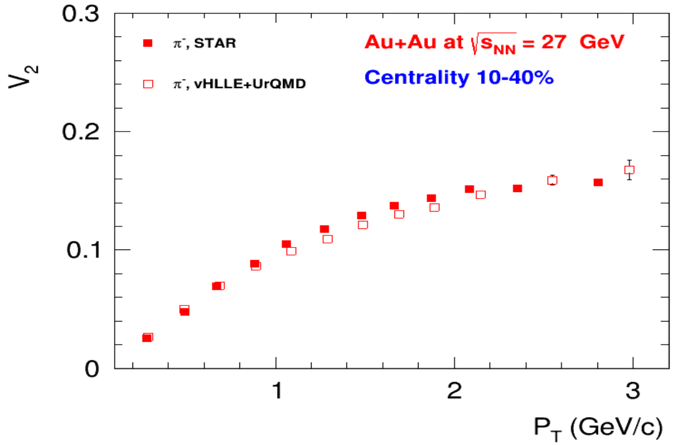
Reasonable agreement between results of vHLLE+UrQMD model and published PHENIX data for 200 GeV including KET/nq scaling

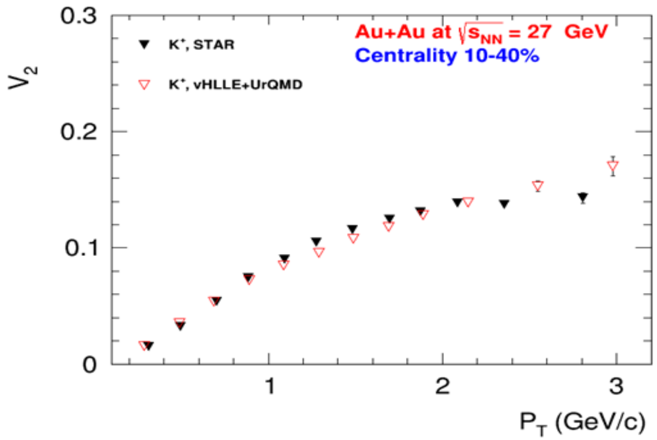
v_2 of charged mesons at RHIC BES ($\sqrt{s_{NN}}$ = 27 GeV)





STAR data: Phys. Rev. C 93 (2016) 14907

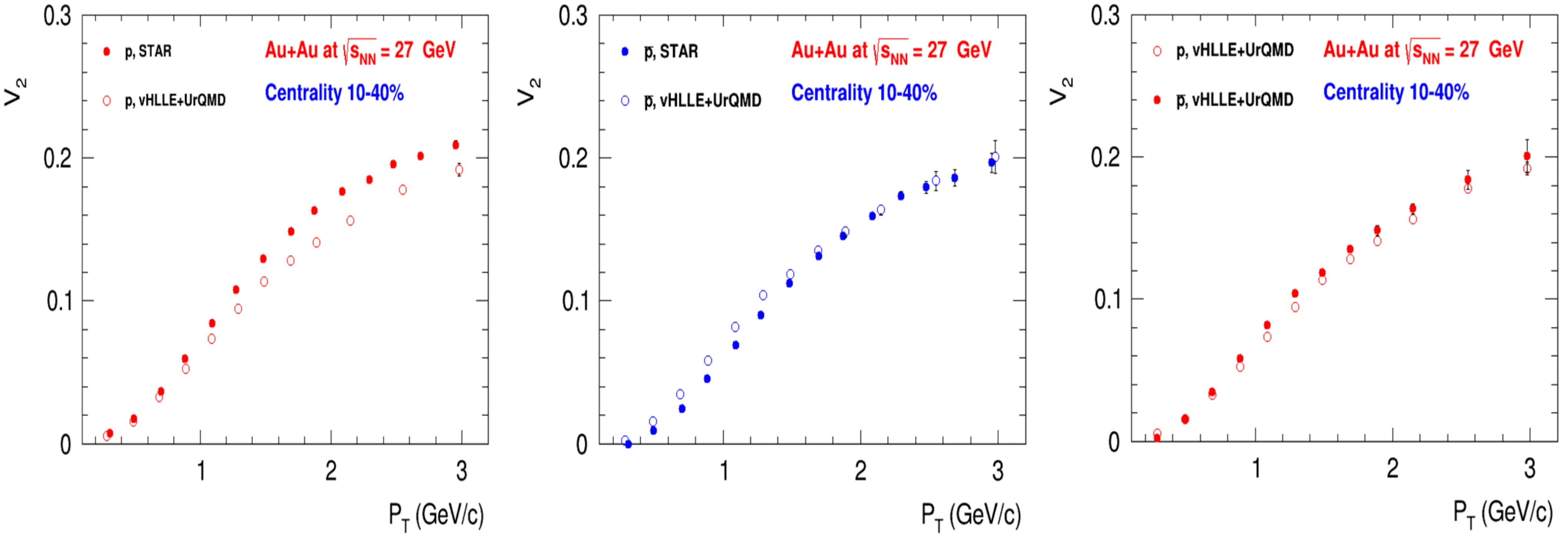




reasonable agreement between vHLLE+UrQMD and data for charged pions and kaons

v_2 of (anti)protons at RHIC BES ($\sqrt{s_{NN}}$ = 27 GeV)

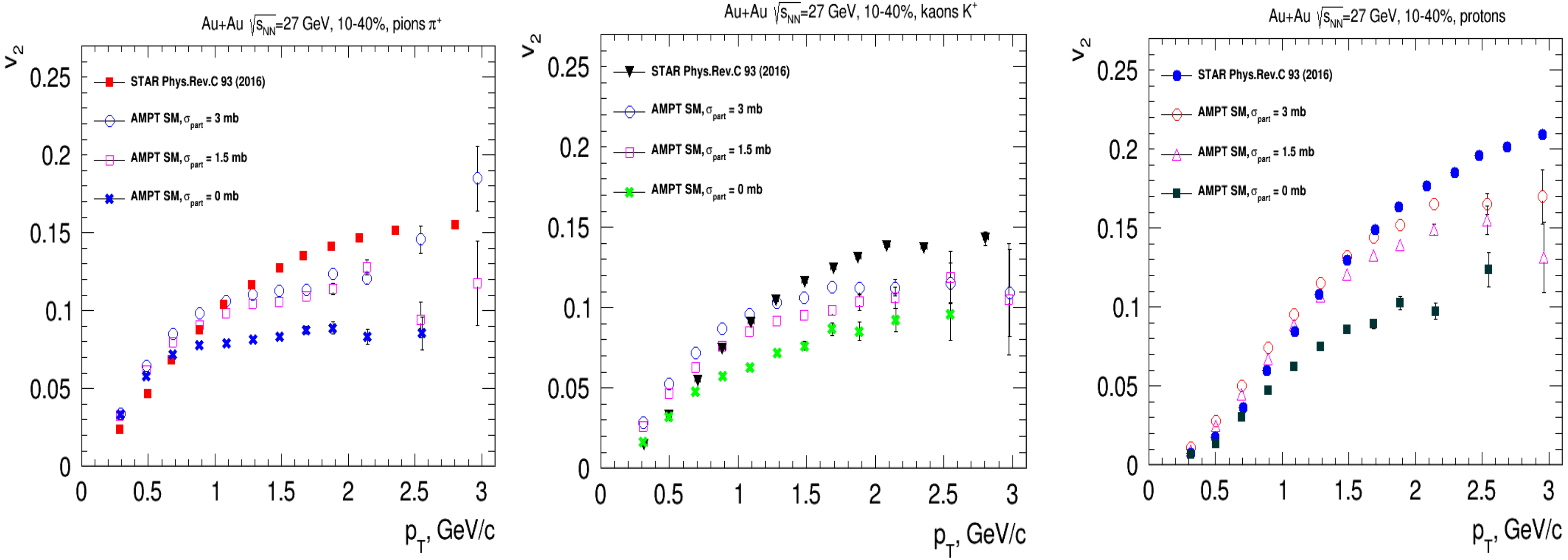
STAR data: Phys. Rev. C 93 (2016) 14907



Difference between results from vHLLE+UrQMD model and data for protons and antiprotons
Model predicts that v_2 (protons) < v_2 (antiprotons) , data show v_2 (protons) > v_2 (antiprotons)
and the difference is growing with decreasing of collision energy.

AMPT: v_2 of identified hadrons at RHIC BES ($\sqrt{s_{NN}}$ = 27 GeV)

STAR data: Phys. Rev. C 93 (2016) 14907



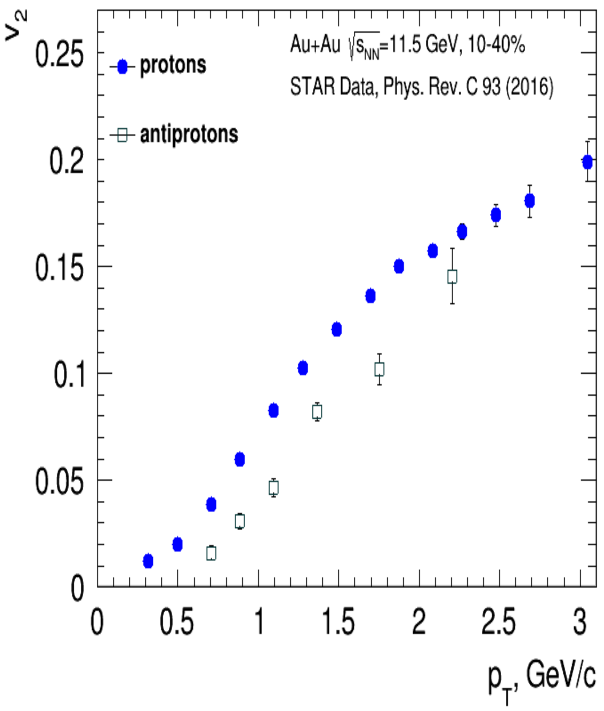
Difference between results from AMPT model SM and data for all particles – tunning of parameters?

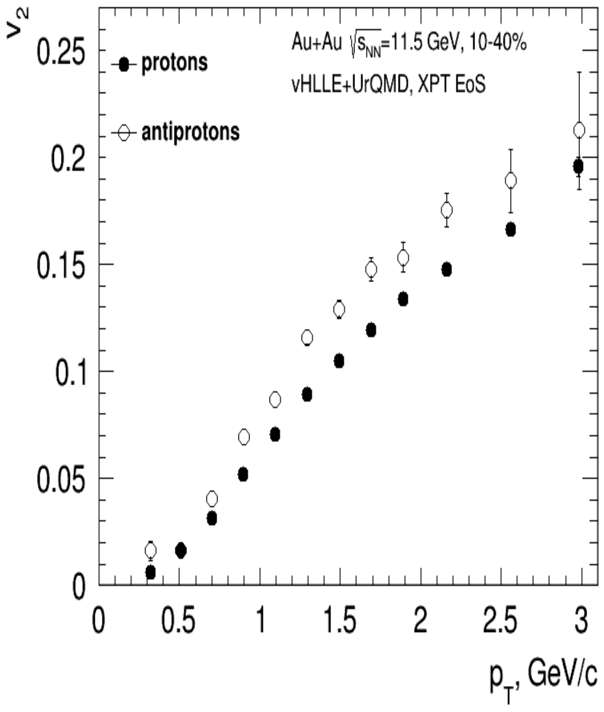
Model also predicts that v_2 (protons) < v_2 (antiprotons) ,

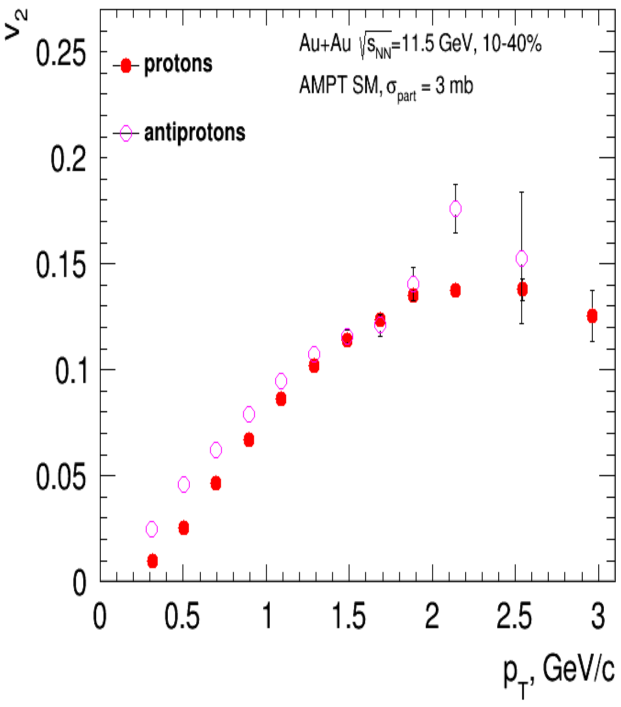
data show v_2 (protons) > v_2 (antiprotons)

v_2 of protons and antiprotons at RHIC BES ($\sqrt{s_{NN}}$ = 11.5 GeV)

STAR data: Phys. Rev. C 93 (2016) 14907

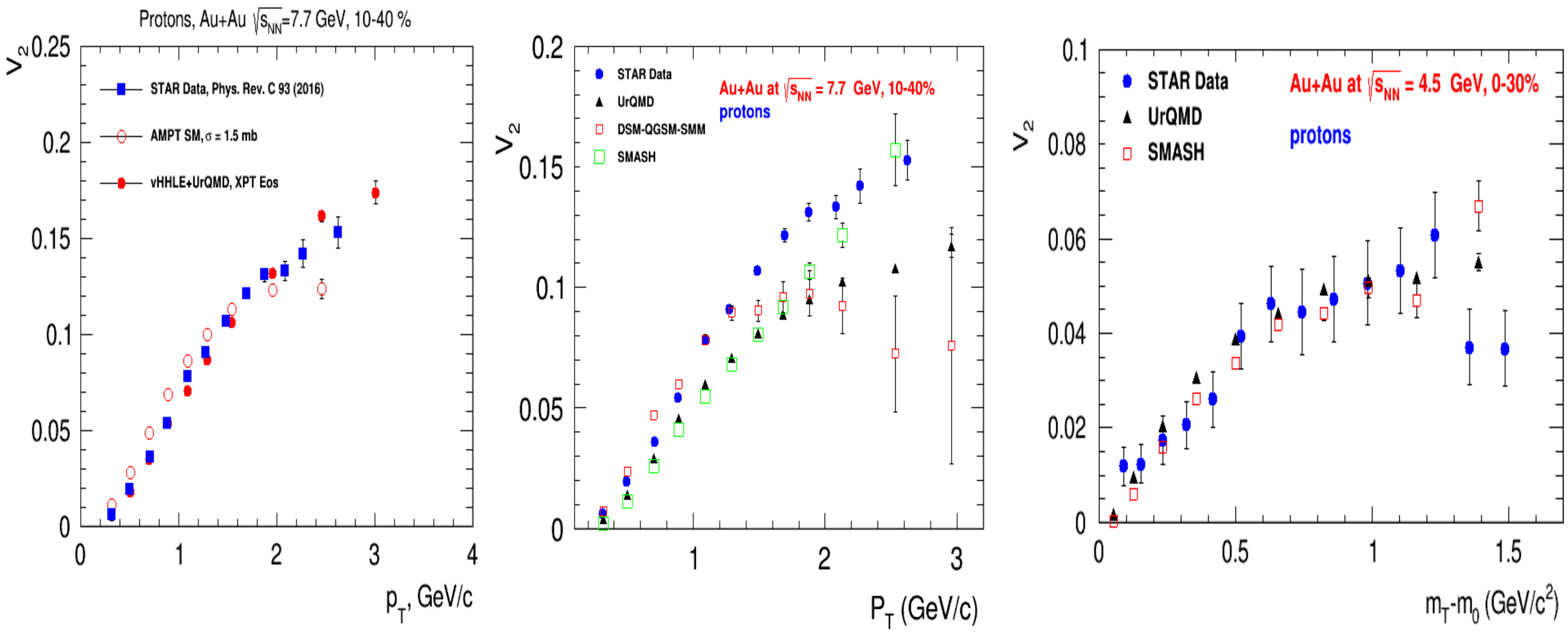






Models AMPT and vHLLE+UrQMD predicts also predicts that v_2 (protons) < v_2 (antiprotons) , data show v_2 (protons) > v_2 (antiprotons)

Elliptic flow: Models vs Data comparison for NICA energy range



Pure String/Hadronic Cascade models (no QGP phase) give smaller v_2 signal compared to STAR data for Au+Au $\sqrt{s_{NN}}$=7.7-11.5 GeV and models give similar v_2 signal compared to STAR data for Au+Au $\sqrt{s_{NN}}$=4.5 GeV.

Summary

- We performed a high statistics simulations with hybrid models (vHLLE+UrQMD and AMPT) for several points in collision energy from RHIC BES program.

- The events were analysed in a similar way as the real experimental data and results were compared with STAR published resuls of v2 for charged pions, kaons and (anti)protons.

- The results from vHLLE+UrQMD model are in a better agreement with experimental data than for AMPT (tunning of the input parameters?)
Both models in the present configuration fails to reproduce the difference between elliptic flow signal of particles and antiparticles: models predict
that v_2 (protons) < v_2 (antiprotons) , data show v_2 (protons) > v_2 (antiprotons)

Model/Data comparison for NICA energy range (4-11 GeV):
Pure String/Hadronic Cascade models (no QGP phase) give smaller v_2 signal compared to STAR data for Au+Au $\sqrt{s_{NN}}$=7.7-11.5 GeV and
models give similar v_2 signal compared to STAR data for Au+Au $\sqrt{s_{NN}}$=4.5 GeV.

Thank you for your attention!

Anisotropic Flow in Heavy-Ion Collisions: 1988

Provides reliable estimates of pressure & pressure gradients

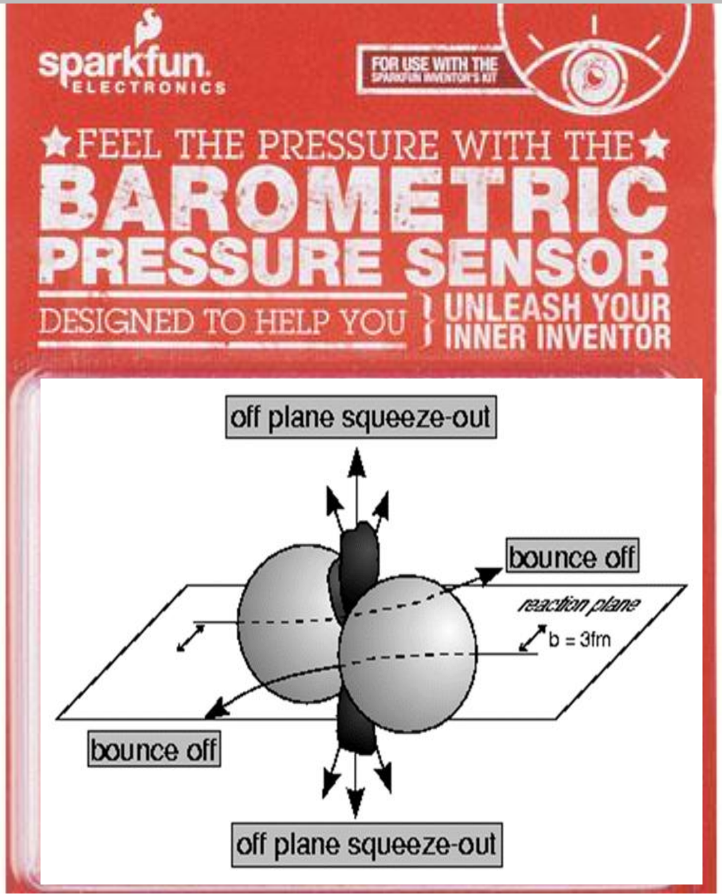
Can address questions related to thermalization

Gives insights on the transverse dynamics of the Medium

Provides access to the transport properties of the medium: EOS, sound speed (c_s), viscosity, etc

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

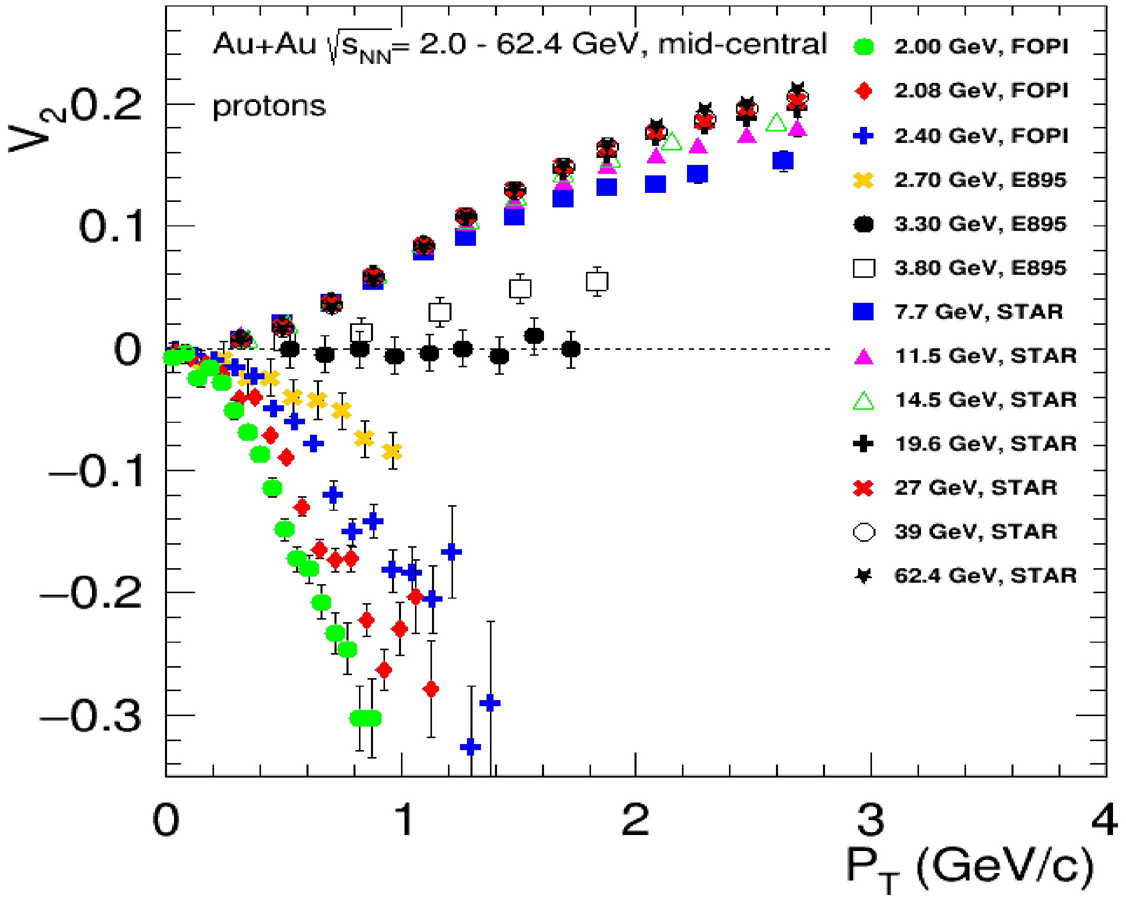
Fourier Expansion for azimuthal anisotropy,
Cheuk-Yin WONG , Physics Letters, 88B, p 39 (1979)



Excitation function of differential elliptic flow

EPJ Web Conf. 204 (2019) 03009

FOPI (15-29%)
E895 (12-25%)
STAR (10-40%)



High precision differential measurements of anisotropic flow?