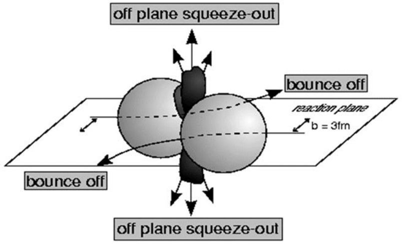
Collective Flow at High Baryon Density

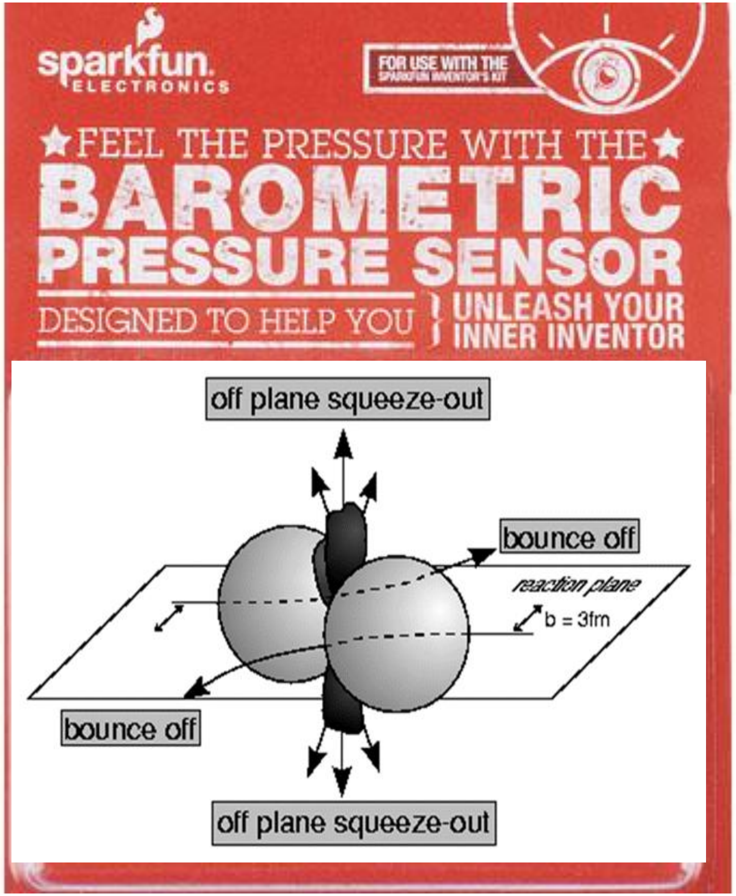
Arkadiy Taranenko, Petr Parfenov (VBLHEP JINR, NRNU MEPhI)



Modern Physics of Compact Stars and Relativistic Gravity 2023 (MPCS-2022), Yerevan , Armenia, September 14-16, 2023

One want to see a probe (phenomena) which is

- Provides reliable estimates of pressure & pressure gradients
- Can address questions related to thermalization
- Gives insides on the transverse dynamics of the medium
- Provides access to the properties of the medium – EOS, viscosity , etc
- Well calibrated : measured at Ganil (MSU), SIS, AGS, SPS, RHIC, LHC energies

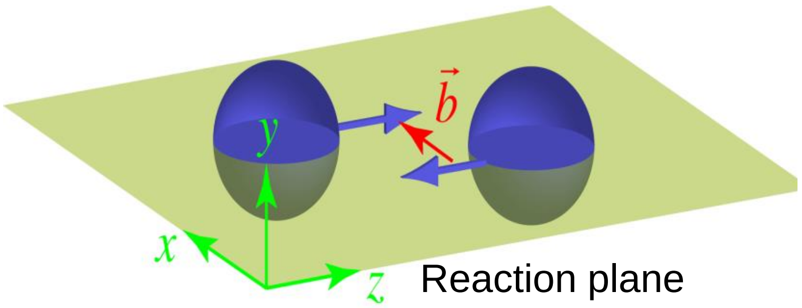


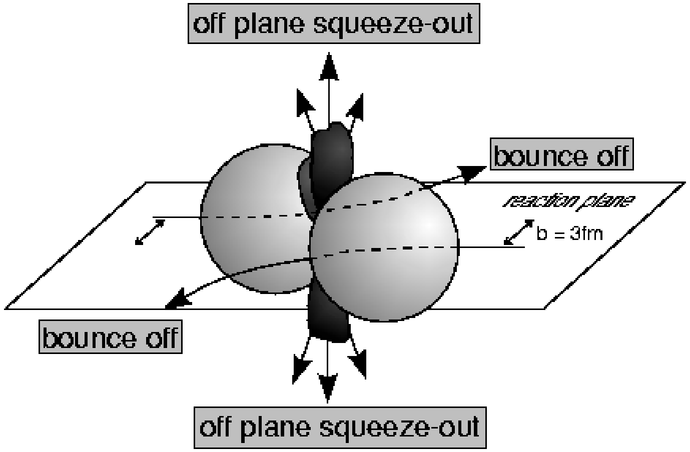
Anisotropic Flow in Heavy-Ion Collisions

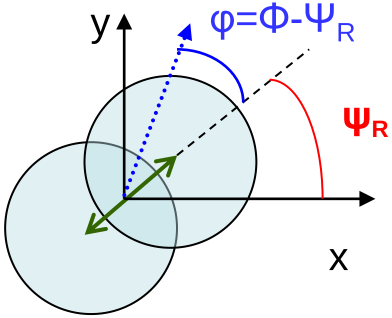
“Squeeze-Out” - First Elliptic flow signal in HIC

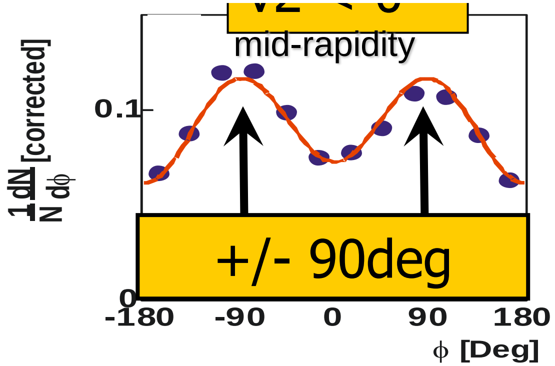
Diogene, M. Demoulins et al., Phys. Lett. B241, 476 (1990)

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

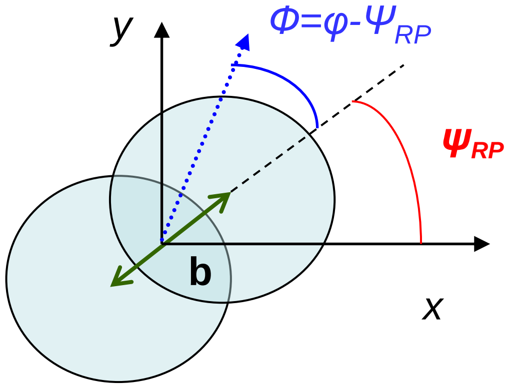






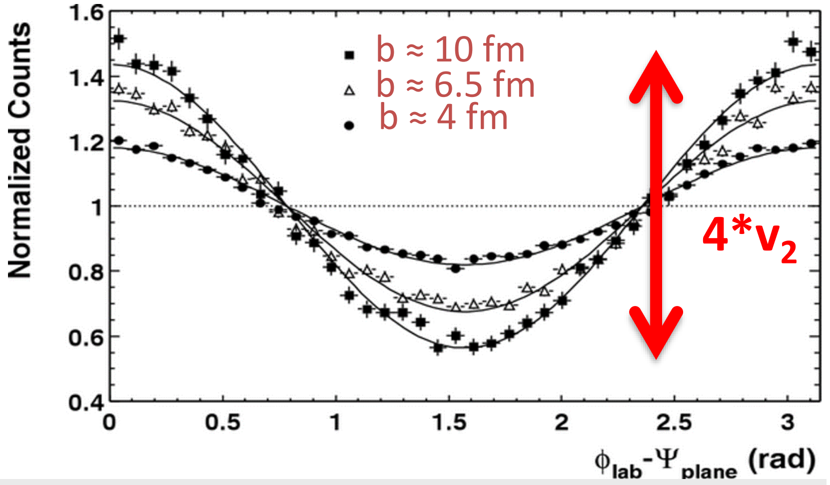


Azimuthal anisotropy of particles at HIC



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

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



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

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

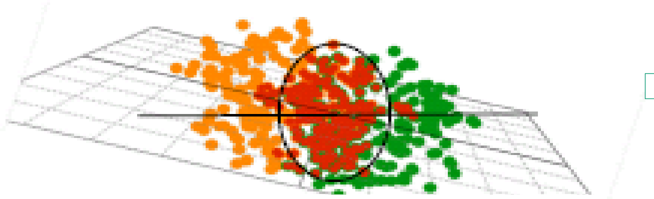
$$v_n=\left\langle\cos\left[n(\varphi-\Psi_{RP})\right]\right\rangle$$

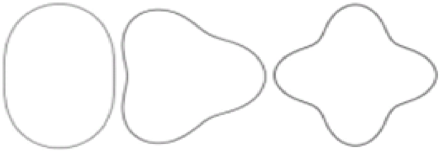
- Fourier coefficients v_n quantify anisotropic flow:

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 at RHIC-LHC



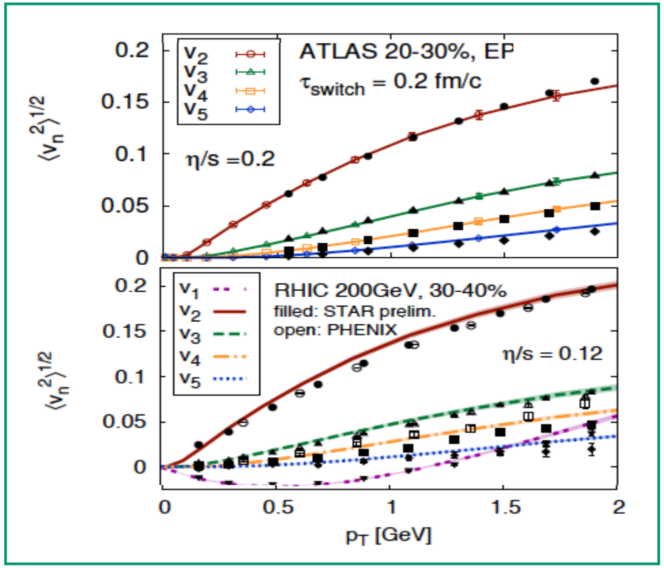


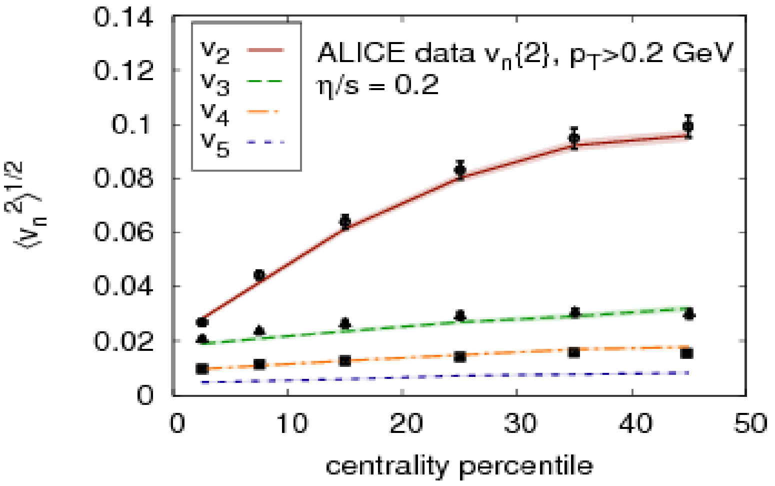
$$\epsilon_n = \sqrt{\frac{\langle r^n \cos n\phi \rangle + \langle r^n \sin n\phi \rangle}{\langle r^n \rangle}}$$

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

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

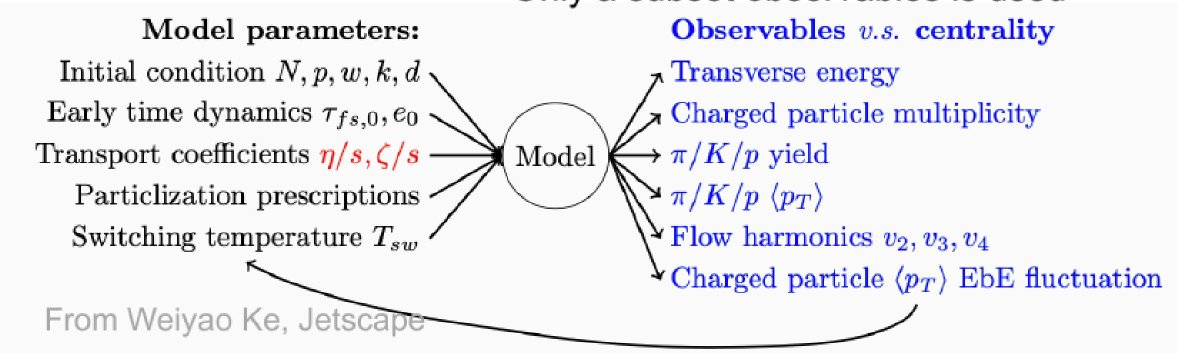




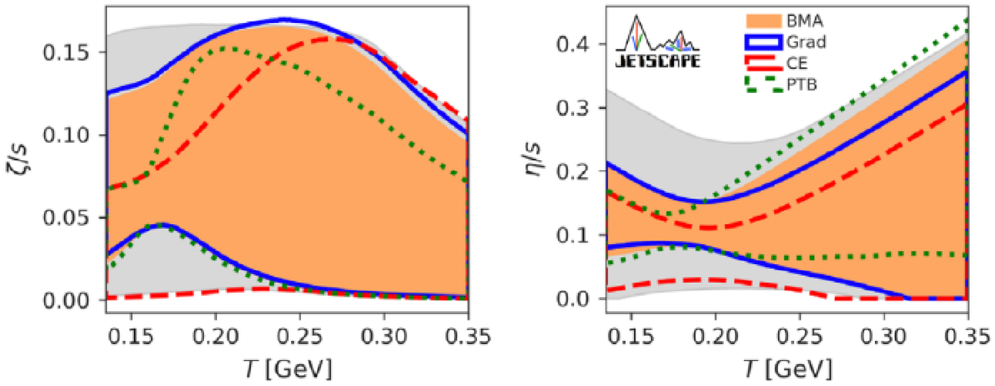
State-of-the-art modeling of HI collisions

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

Only a subset observables is used



- Detailed temperature dependence of viscosity!

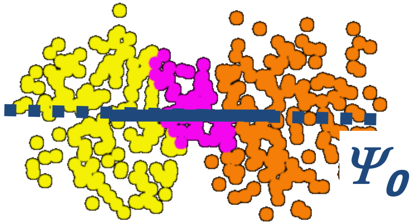


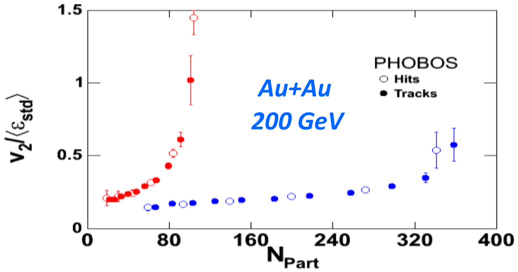
Jetscape PRL.126.242301
Trjactum PRL.126.202301

Major uncertainty: initial condition and pre-hydro phase

2001-2005

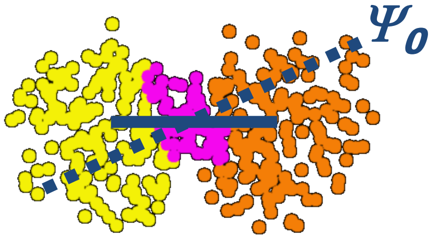
$$\varepsilon_{\text{std}} = \frac{\sigma_y^2 - \sigma_x^2}{\sigma_x^2 + \sigma_y^2}$$

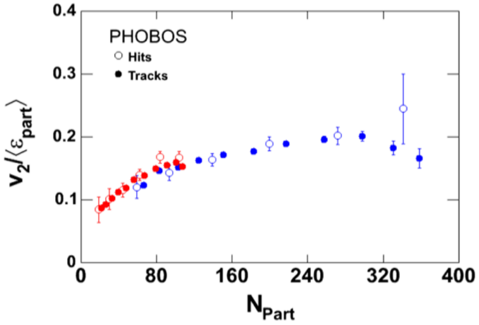




2005-2011

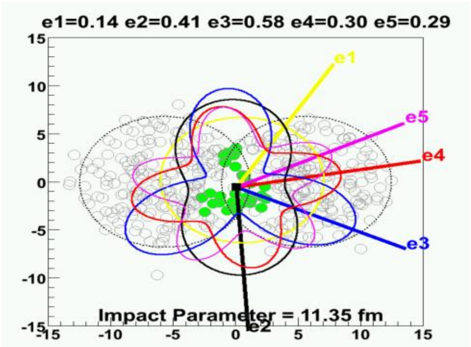
$$\langle\epsilon_{\text{part}}\rangle = \frac{\sqrt{(\sigma_y^2 - \sigma_x^2)^2 + 4\sigma_{xy}^2}}{(\sigma_y^2 + \sigma_x^2)}$$

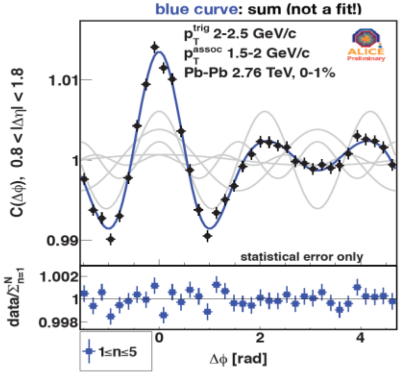




2011-2012

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

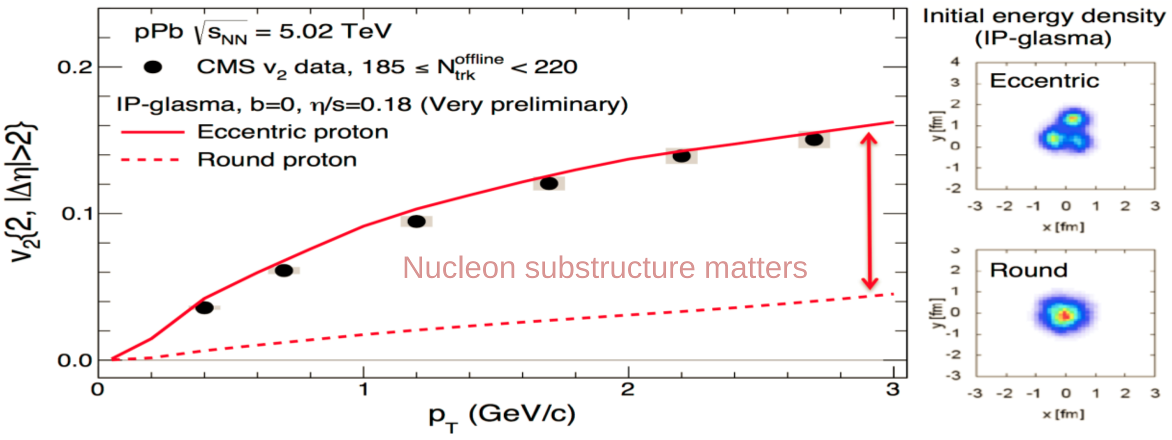




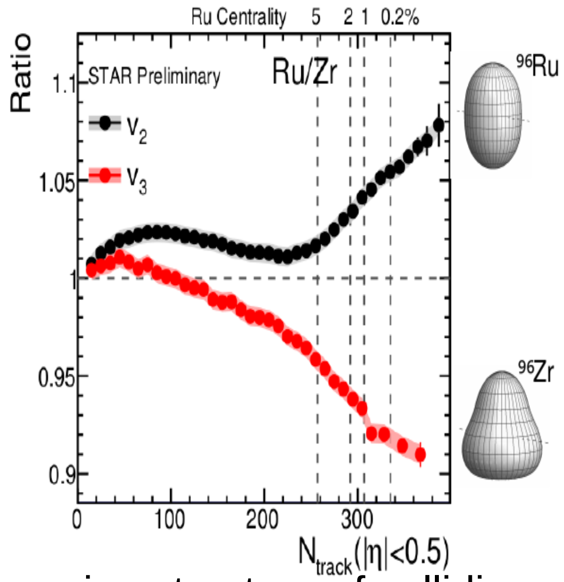
For "lumpy" *profile* $\varphi \neq \varphi + \pi$

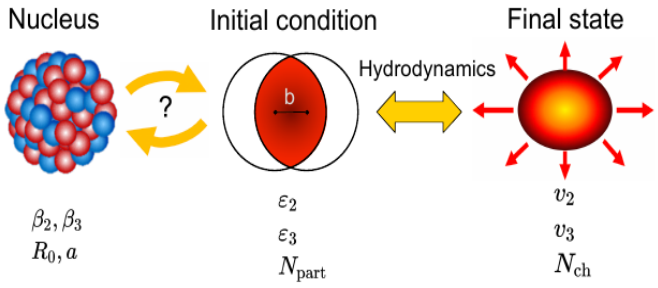
Odd harmonics $\neq 0$

2011-2016



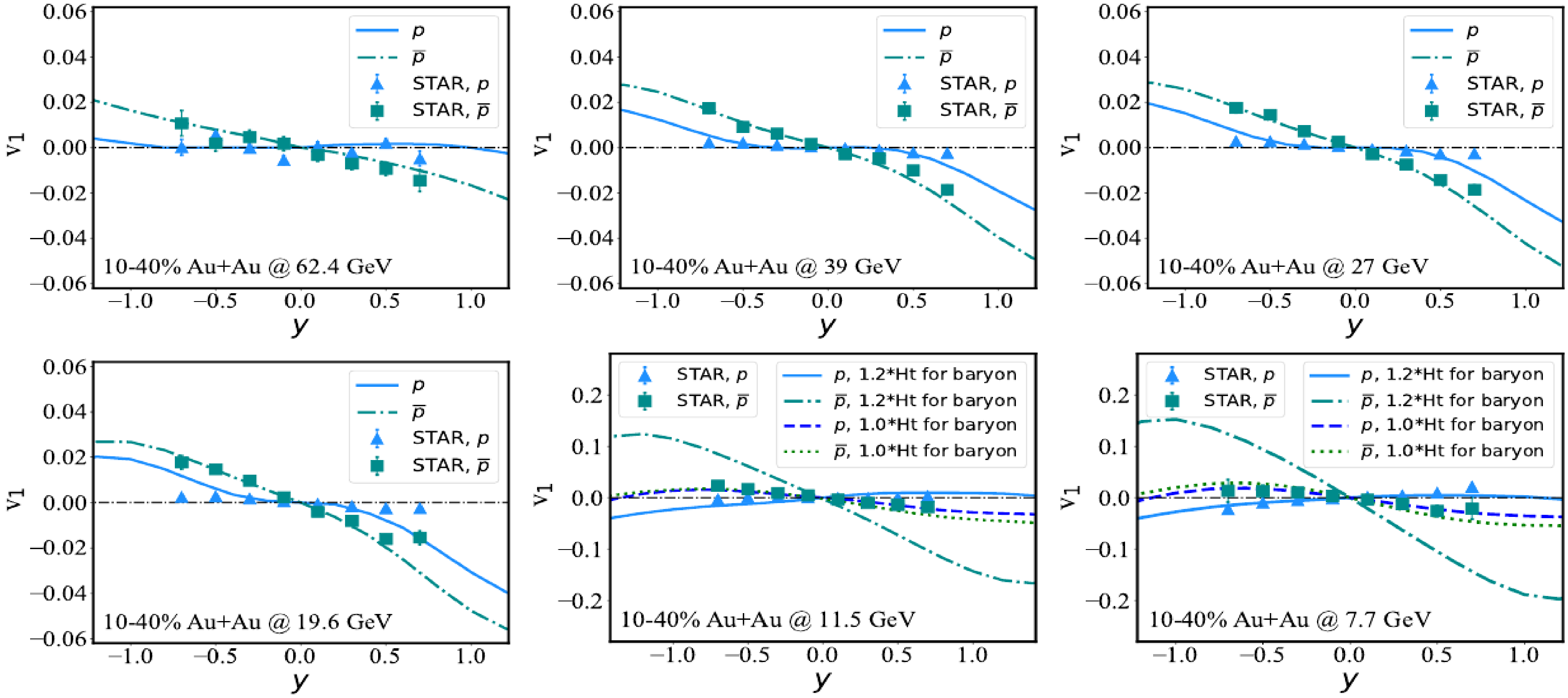
2020-2023





Accessing structure of colliding nucleus from collectivity?

Directed flow BES

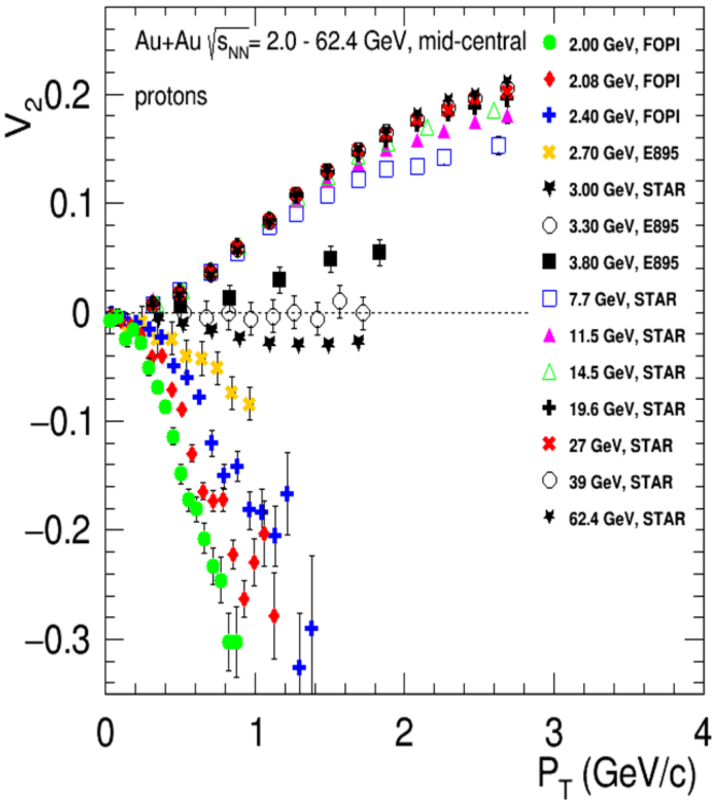


o *include both a tilted deformation of the fireball with respect to the longitudinal direction and a non-zero longitudinal flow velocity gradient in the initial state*

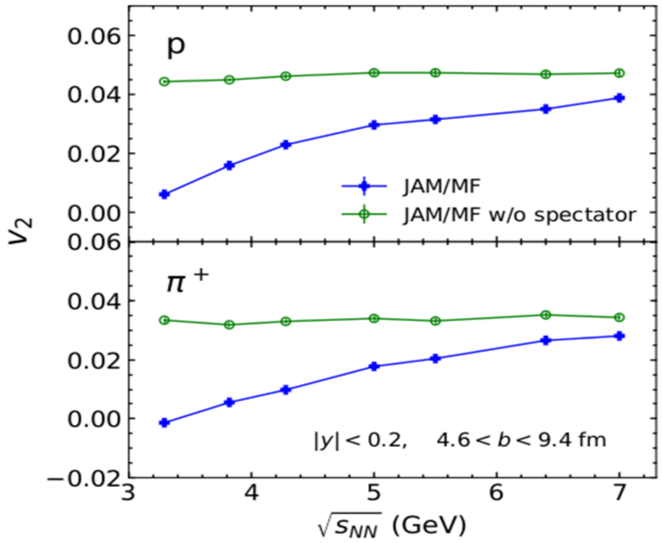
Phys.Rev.C 107 (2023) 3, 3 • e-Print: 2301.02960 [nucl-th]

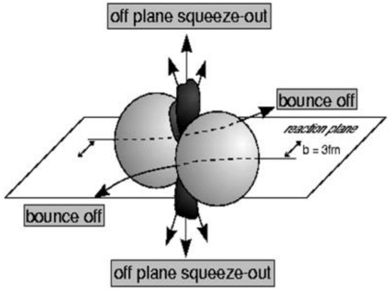
Beam Energy Dependence of Elliptic Flow (v_2)

EPJ Web Conf. 204 (2019) 03009



Phys. Rev. C 97, 064913 (2018)



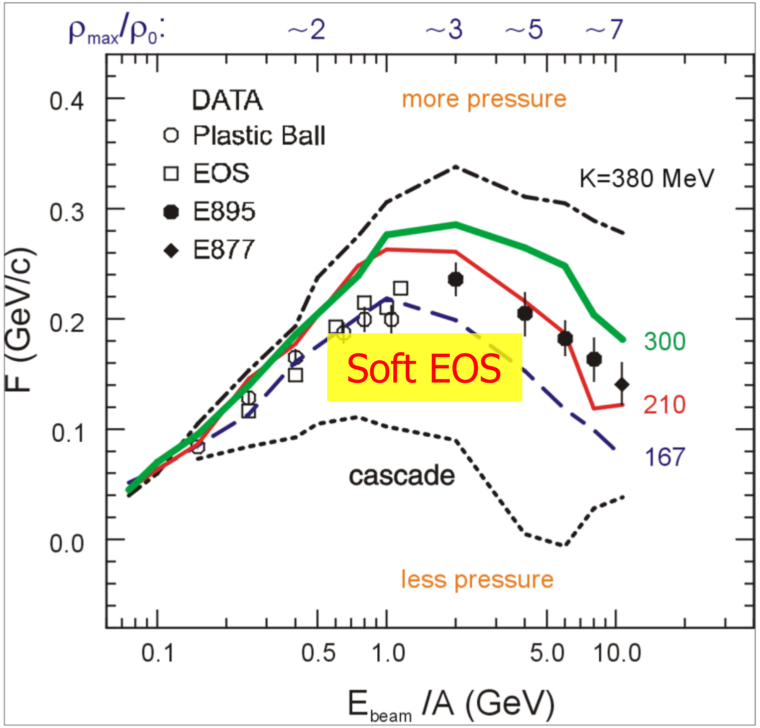


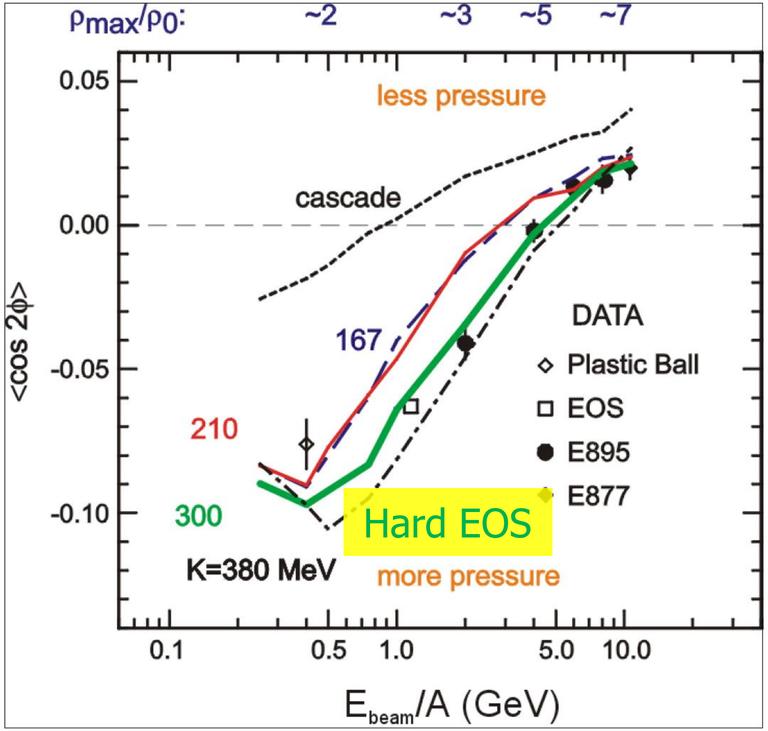
Passage time: **$2R/(\beta_{cm}\gamma_{cm})$**
Expansion time: **R/c_s**
$c_s = c\sqrt{dp/d\varepsilon}$ - speed of sound

- **Strong energy dependence of v_2 at $\sqrt{s_{NN}}$ = 2-11 GeV**
  - $v_2 \approx 0$ at $\sqrt{s_{NN}}$ = 3.3 GeV and negative below

Nuclear incompressibility from collective proton flow

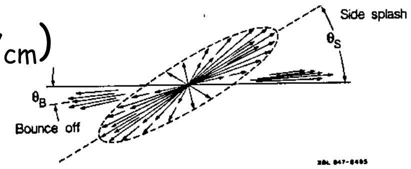
P. Danielewicz, R. Lacey, W.G. Lynch, Science 298 (2002) 1592



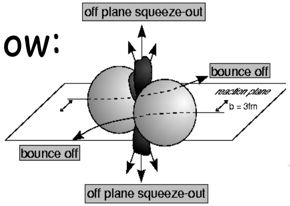


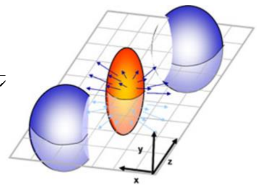
Transverse in-plane flow:

$F = d(p_x/A)/d(y/y_{cm})$



Elliptic flow:

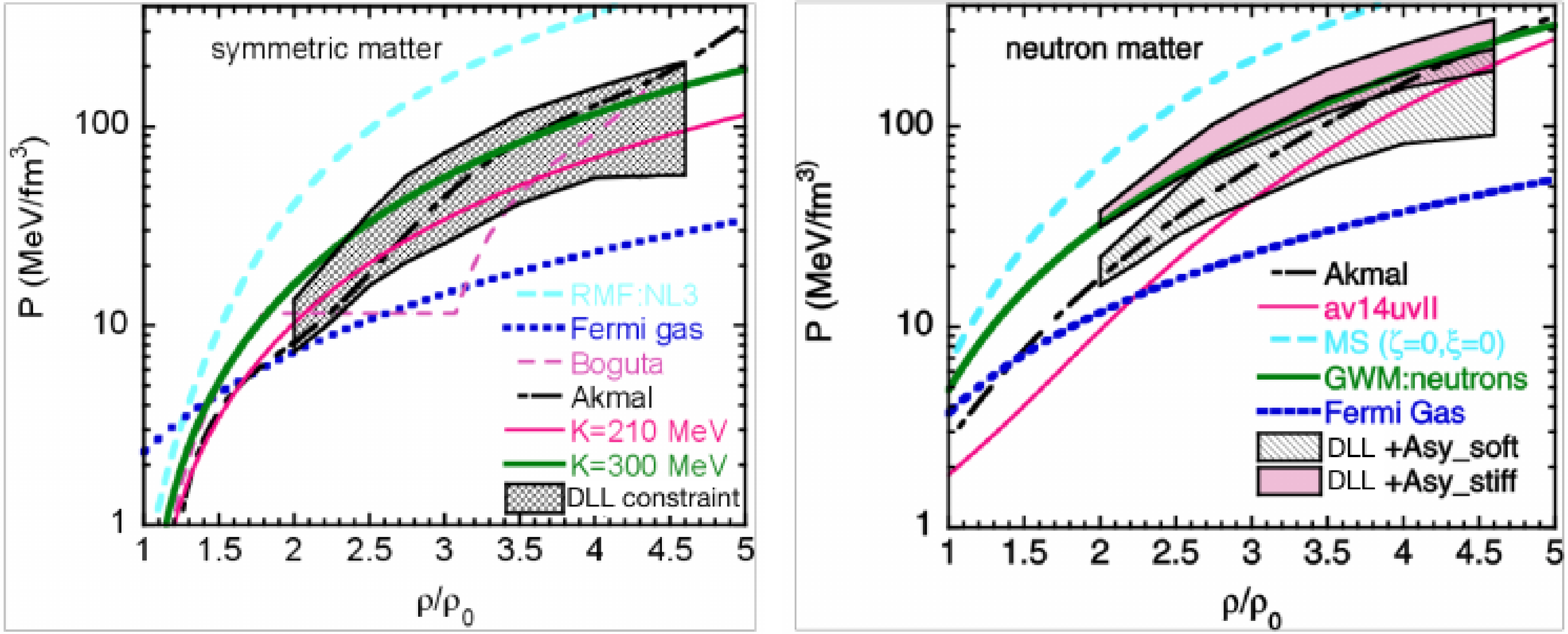




$dN/d\Phi \propto (1 + 2v_1 \cos\Phi + 2v_2 \cos 2\Phi)$

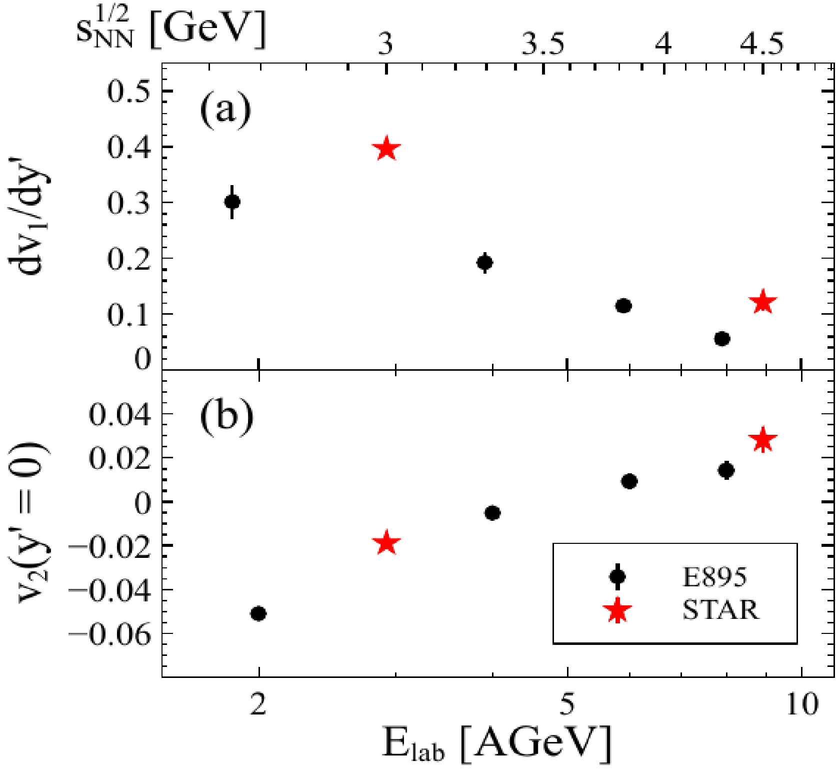
Nuclear incompressibility from collective proton flow

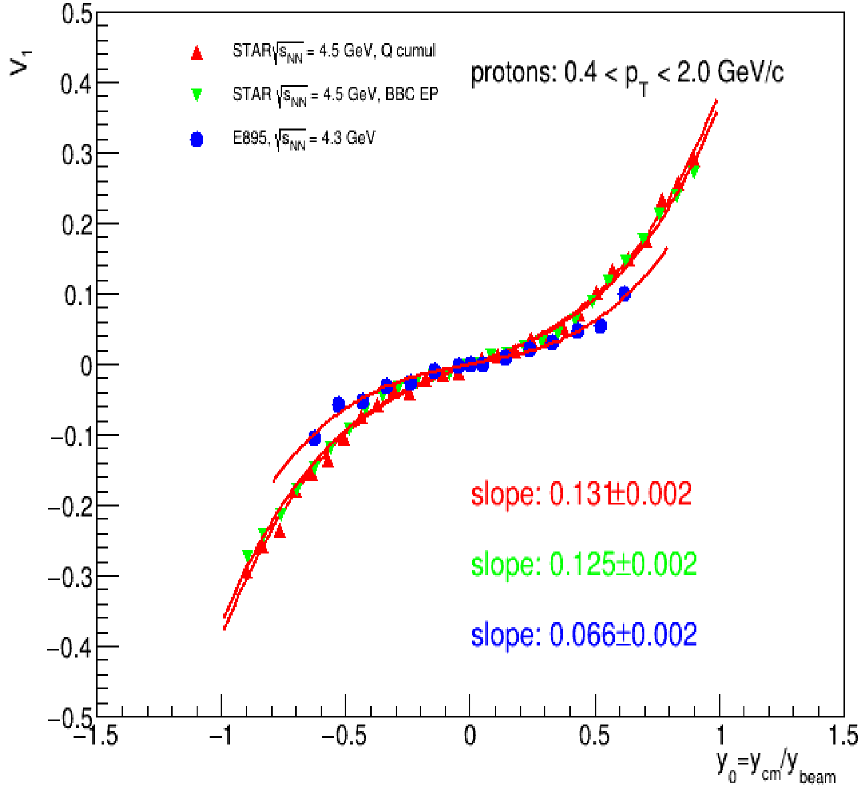
P. Danielewicz, R. Lacey, W.G. Lynch, Science 298 (2002) 1592



Sensitivity of Au+Au collisions to the symmetric nuclear matter equation of state at 2–5 nuclear saturation densities

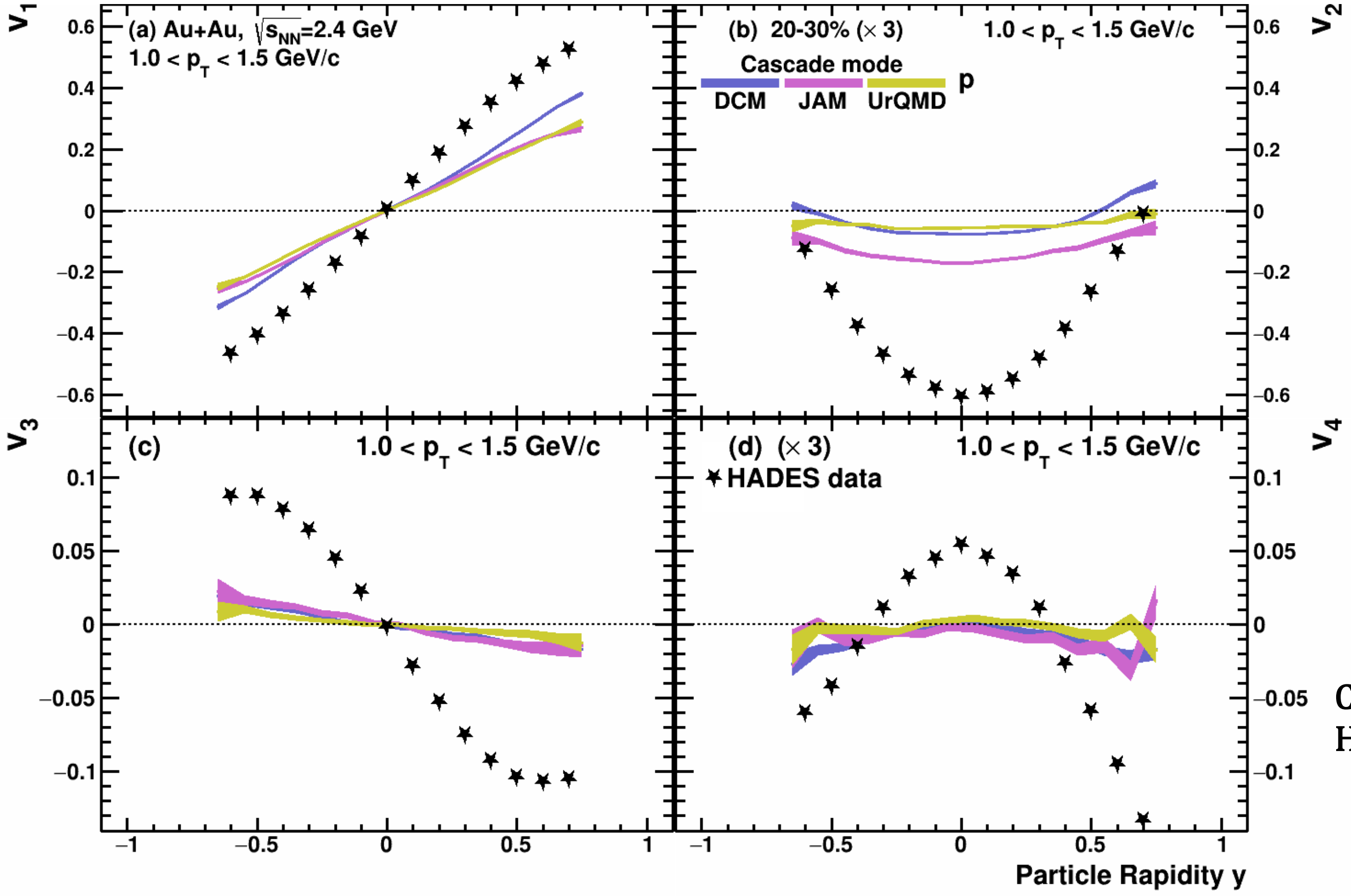
Dmytro Oliinychenko,[1,*] Agnieszka Sorensen,[1,†] Volker Koch,[2] and Larry McLerran[1]
[1]Institute for Nuclear Theory, University of Washington, Box 351550, Seattle, Washington 98195, USA
[2]Lawrence Berkeley National Laboratory, 1 Cyclotron Road, Berkeley, California 94720, USA





The main source of existing systematic errors in v_n measurements is the difference between results from different experiments (for example, FOPI and HADES, E895 and STAR)

$v_n(y)$ in Au+Au $\sqrt{s_{NN}}$=2.4 GeV: cascade models



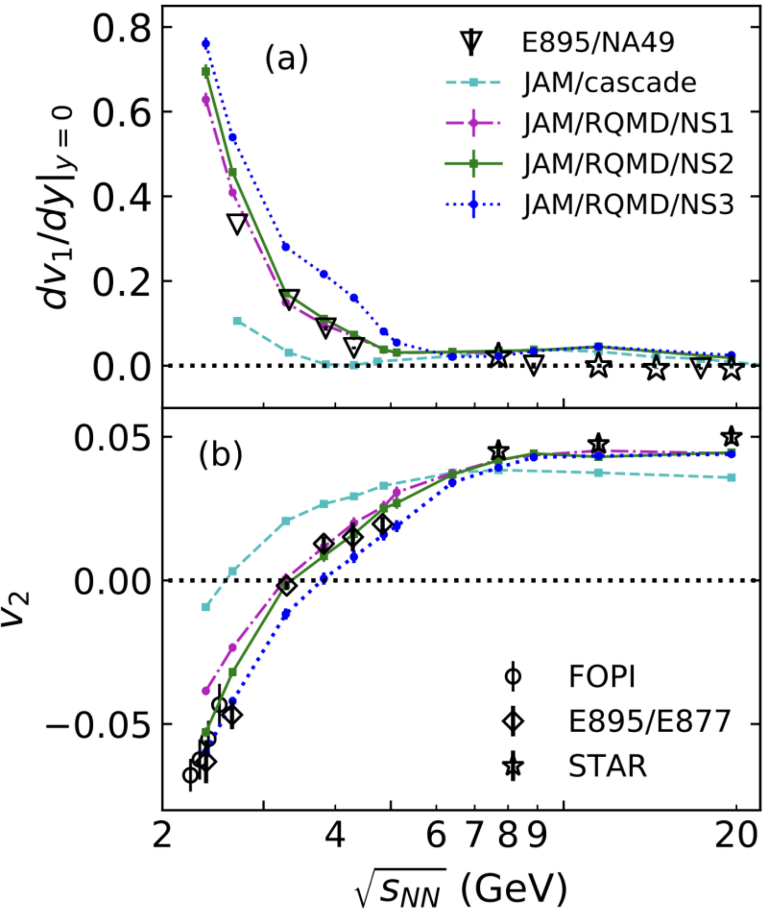
P. Parfenov, Particles 5, no.4, 561-579 (2022)

Kinematic cuts:
$V_{1,3}(y)$: 1.0 < pT < 1.5 GeV/c
$V_{2,4}(y)$: 1.0 < pT < 1.5 GeV/c

Cascade models fail to reproduce HADES experimental data

Anisotropic flow study at $\sqrt{s_{NN}}$=2-4 GeV with JAM model

Y.Nara, et al., Phys. Rev. C 100, 054902 (2019)



To study energy dependence of v_n, JAM microscopic model was selected (ver. 1.90597)

NN collisions are simulated by:

- $\sqrt{s_{NN}}$<4 GeV: resonance production
- 4<$\sqrt{s_{NN}}$<50 GeV: soft string excitations
- $\sqrt{s_{NN}}$>10 GeV: minijet production

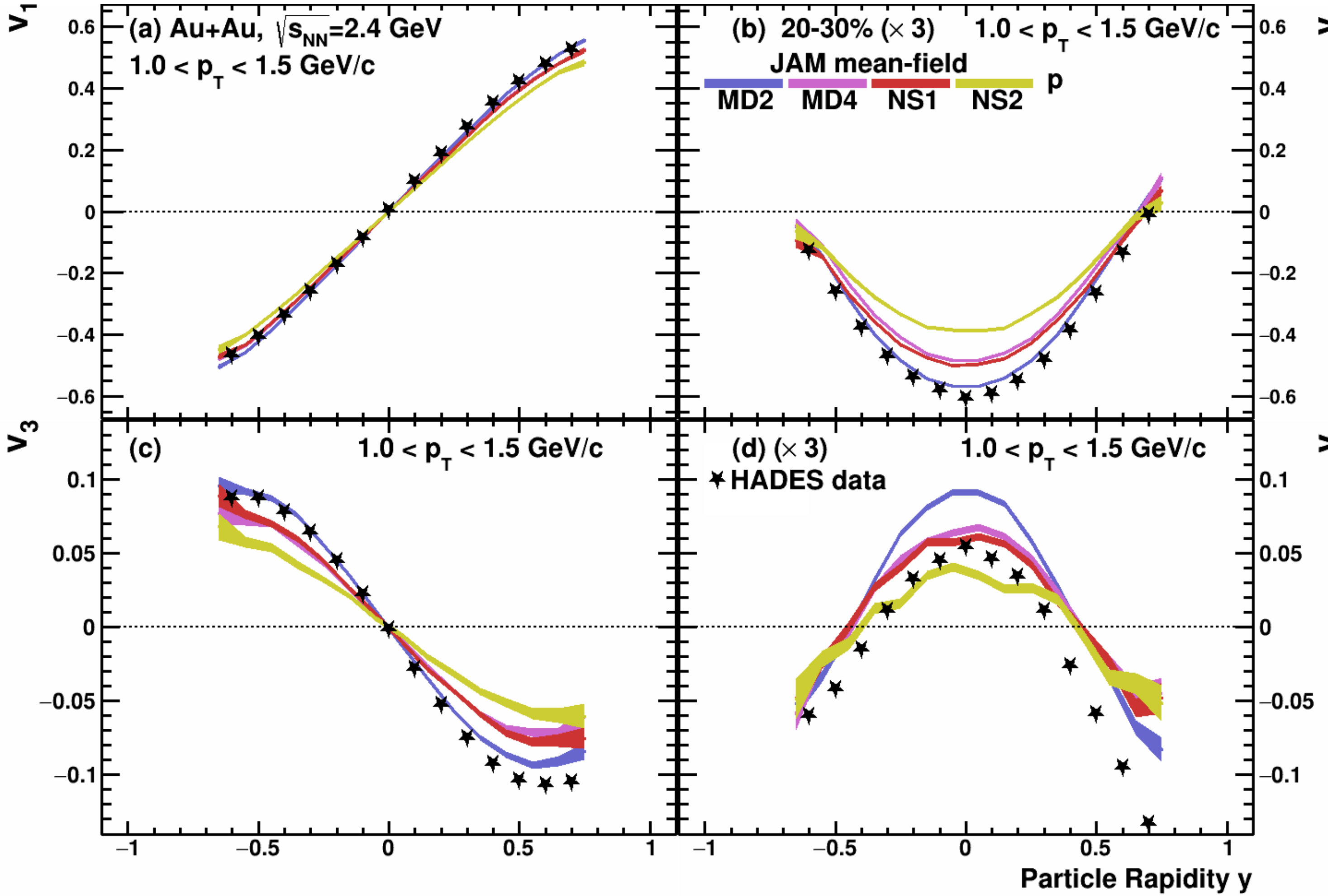
We use RQMD with relativistic mean-field theory (non-linear σ-ω model) implemented in JAM model

Different EOS were used:

- **MD2** (momentum-dependent potential): K=380 MeV, m^*/m=0.65, $U_{opt}(\infty)$=30
- **MD4** (momentum-dependent potential): K=210 MeV, m^*/m=0.83, $U_{opt}(\infty)$=67
- **NS1**: K=380 MeV, m^*/m=0.83, $U_{opt}(\infty)$=95
- **NS2**: K=210 MeV, m^*/m=0.83, $U_{opt}(\infty)$=98

Y.Nara, T.Maruyama, H.Stoecker Phys. Rev. C 102, 024913 (2020)
Y.Nara, H.Stoecker Phys. Rev. C 100, 054902 (2019)

$v_n(y)$ in Au+Au $\sqrt{s_{NN}}$=2.4 GeV: model vs. HADES data

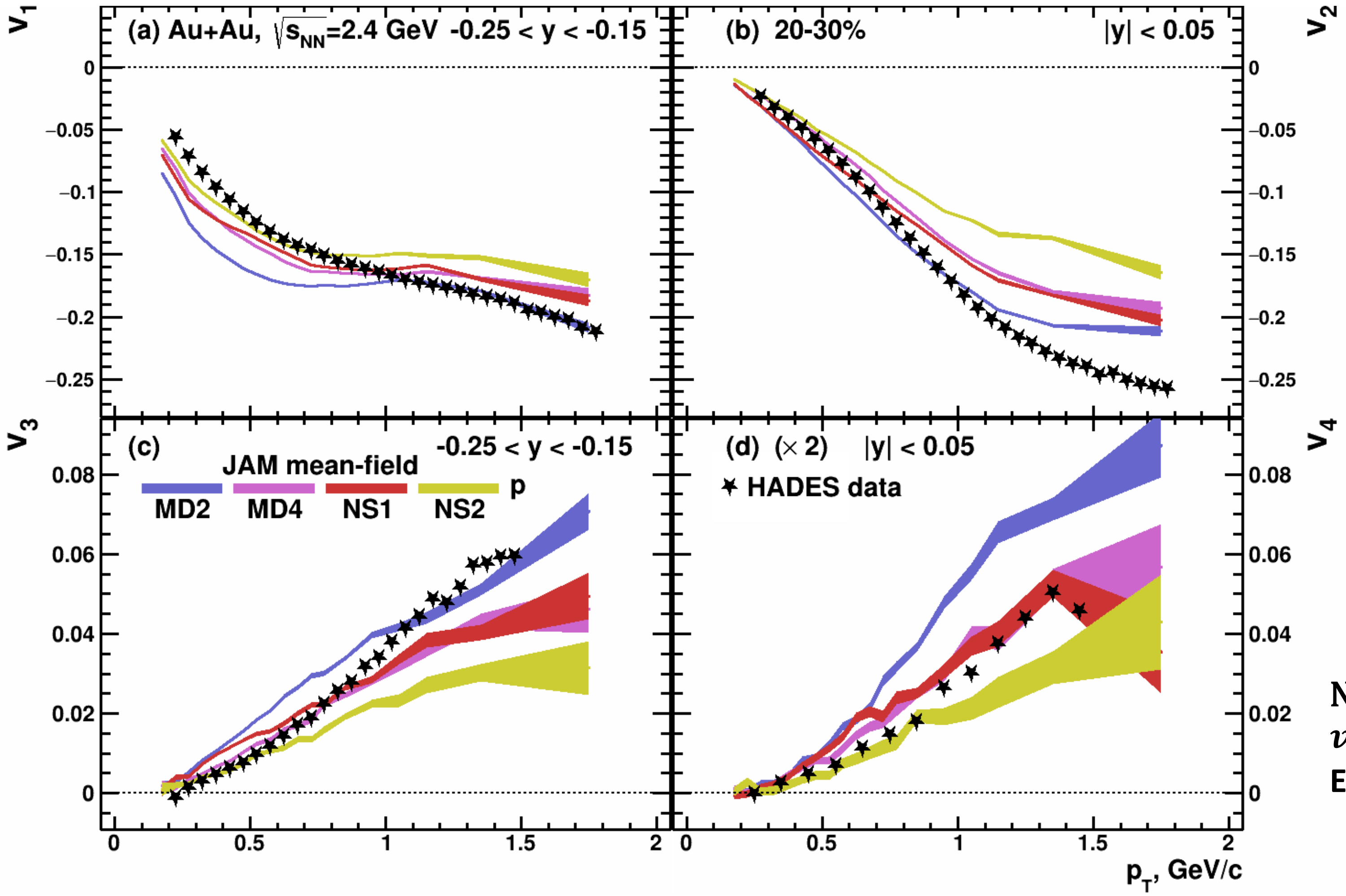


P. Parfenov, Particles 5, no.4, 561-579 (2022)

Kinematic cuts:
$V_{1,3}$(y): 1.0 < pT < 1.5 GeV/c
$V_{2,4}$(y): 1.0 < pT < 1.5 GeV/c

Good agreement for $v_n(y)$
Higher harmonics are more sensitive to different EOS than v_1

$v_n(p_T)$ in Au+Au $\sqrt{s_{NN}}$=2.4 GeV: model vs. HADES data

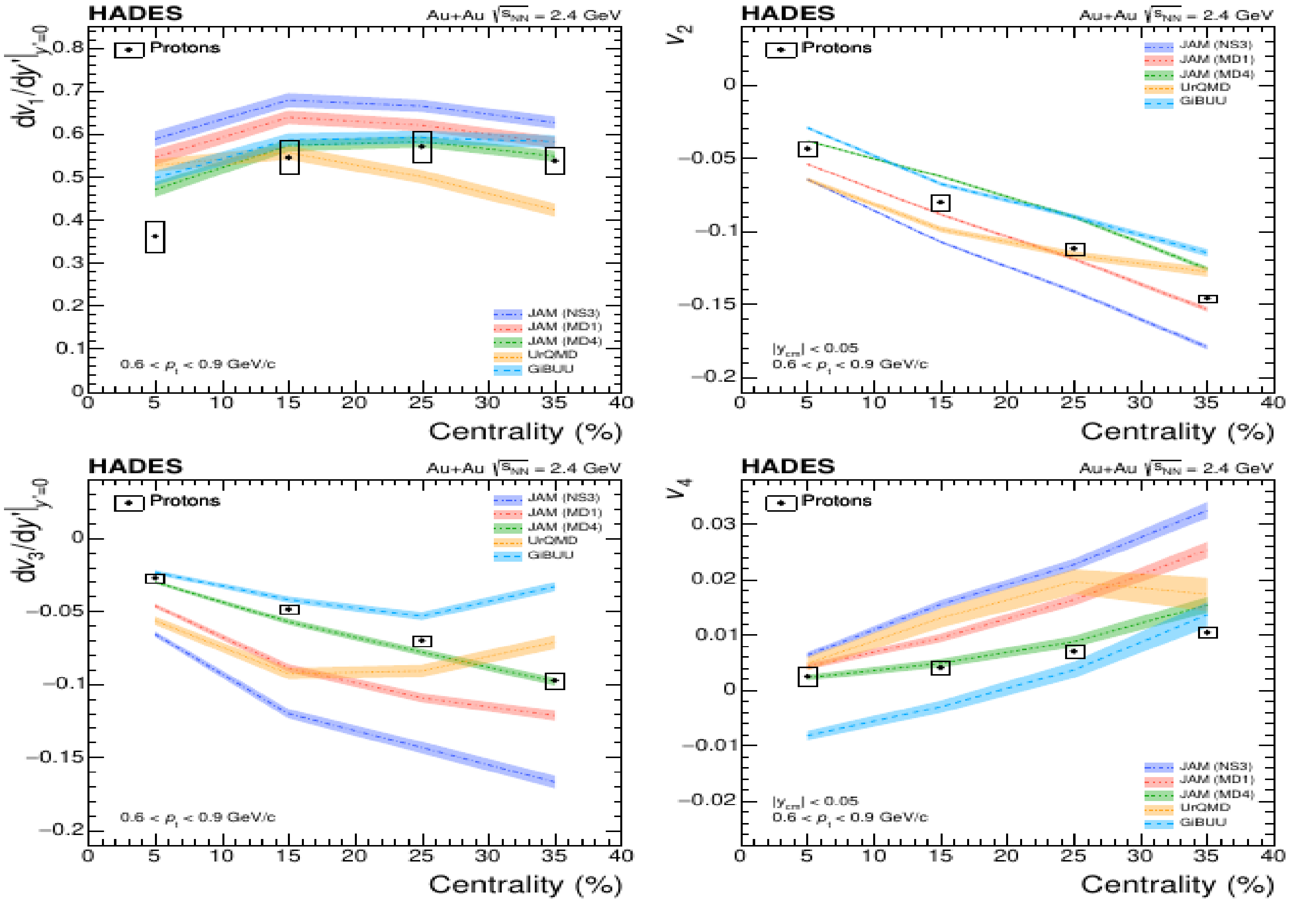


Experimental data points:
Phys. Rev. Lett. **125** (2020) 262301

Kinematic cuts:
$V_{1,3}(p_T)$: -0.25 < y < -0.15
$V_{2,4}(p_T)$: -0.05 < y < 0.05

Not a good agreement for $v_n(p_T)$
$v_{3,4}$ are more sensitive to different EOS than v_1

$v_n(centrality)$ in Au+Au $\sqrt{s_{NN}}$=2.4 GeV: models vs. HADES data



Models and Experimental data from:

Eur.Phys.J.A 59 (2023) 4, 80

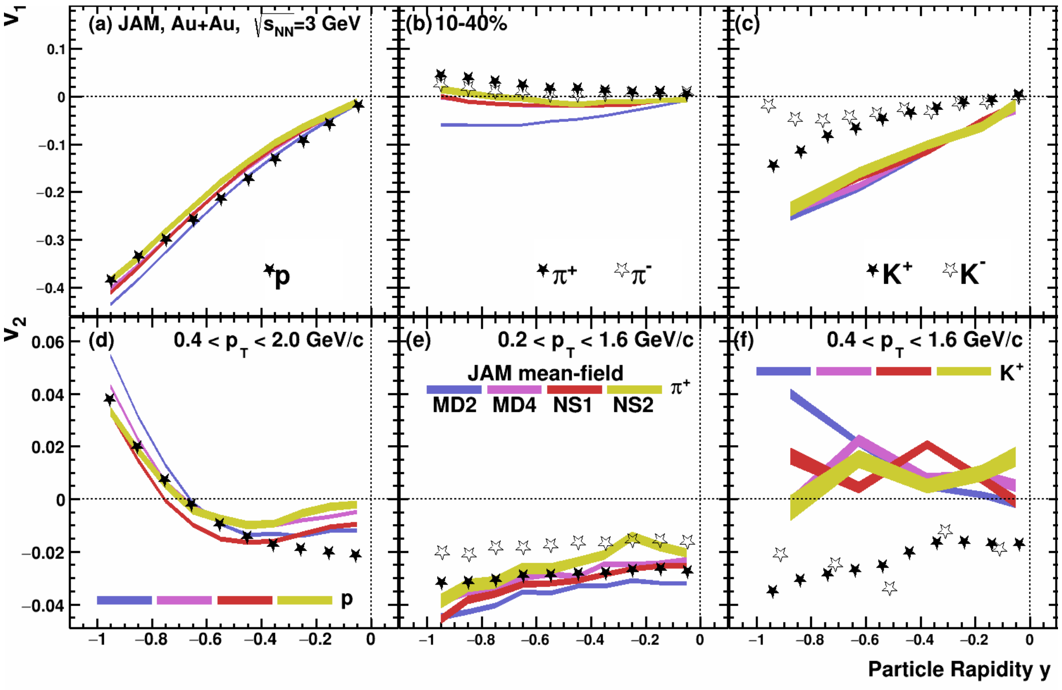
Kinematic cuts:

$V_{1,3}(p_T)$: $-0.25 < y < -0.15$

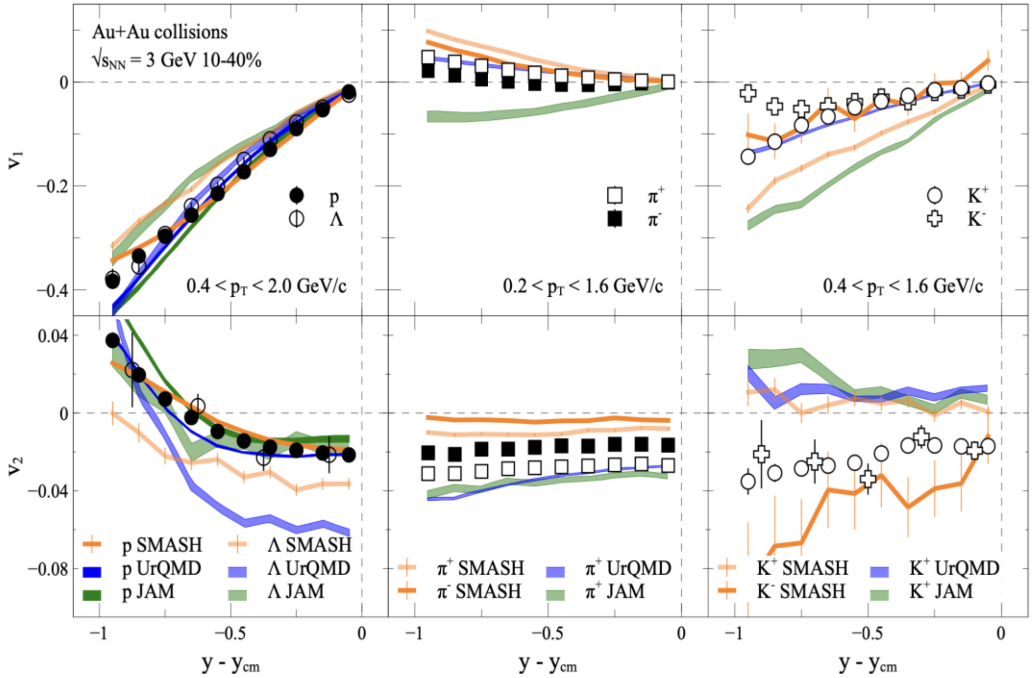
$V_{2,4}(p_T)$: $-0.05 < y < 0.05$

Generally, all models roughly capture the overall magnitude and trend of the measured data.

$v_{1,2}(y)$ in Au+Au $\sqrt{s_{NN}}$=3 GeV: model vs. STAR data



P. Parfenov, Particles 5, no.4, 561-579 (2022)

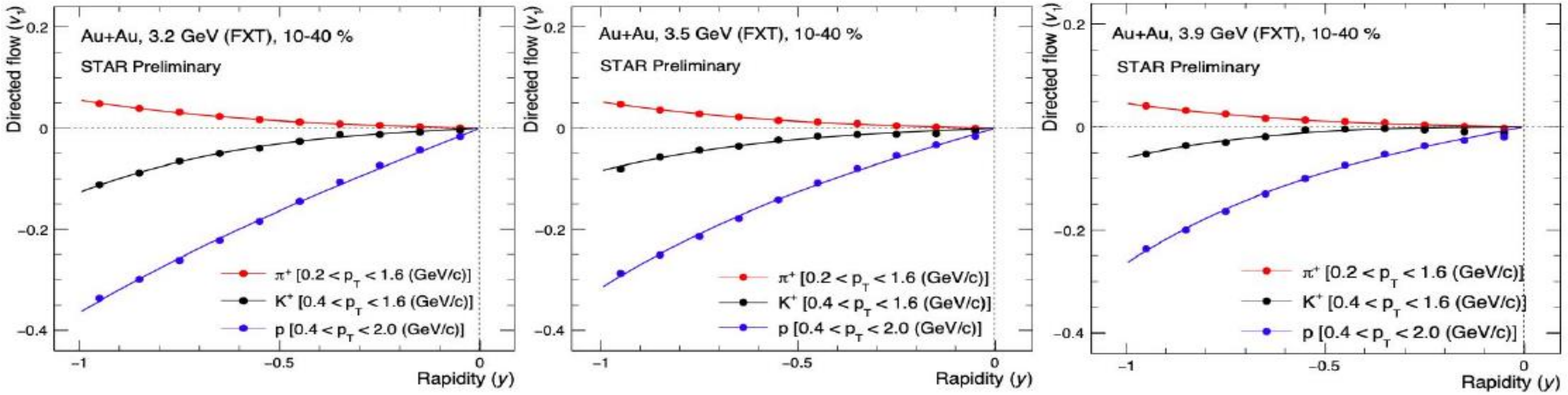


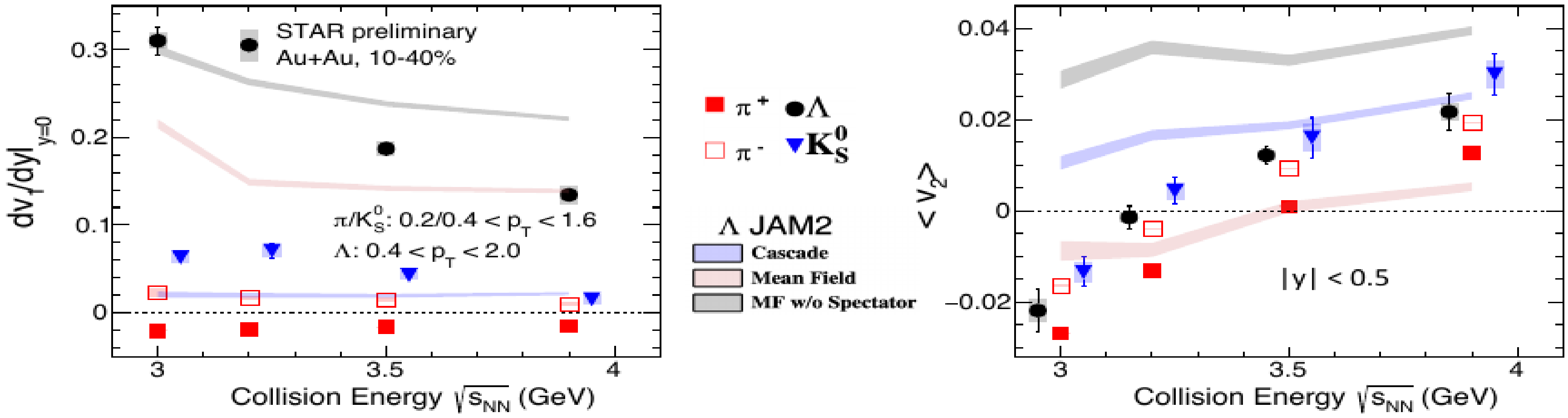
A. Sorensen et. al., arXiv:2301.13253 [nucl-th] (2023)

Models do not describe all particle species equally well

v_1, v_2 of protons are described by JAM, UrQMD (hard EOS) and SMASH (hard EOS with softening at higher densities)

New STAR results from BES – II program were presented at QM2023



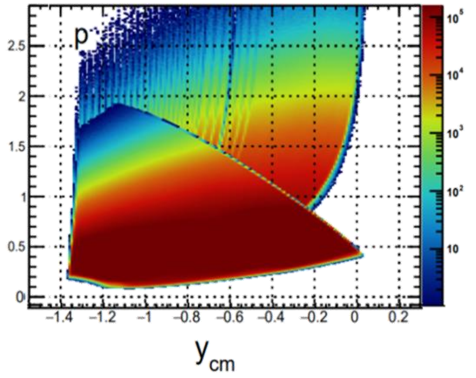


RHIC BES programs

- Data taking by 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

Au+Au @ 3.9 GeV



- A very impressive and successful program with many collected datasets, already available and expected results
- Limitations:
  - ✓ Au+Au collisions only
  - ✓ Among the fixed-target runs, only the 3 GeV data have full mid-rapidity coverage for protons (|y| < 0.5),

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

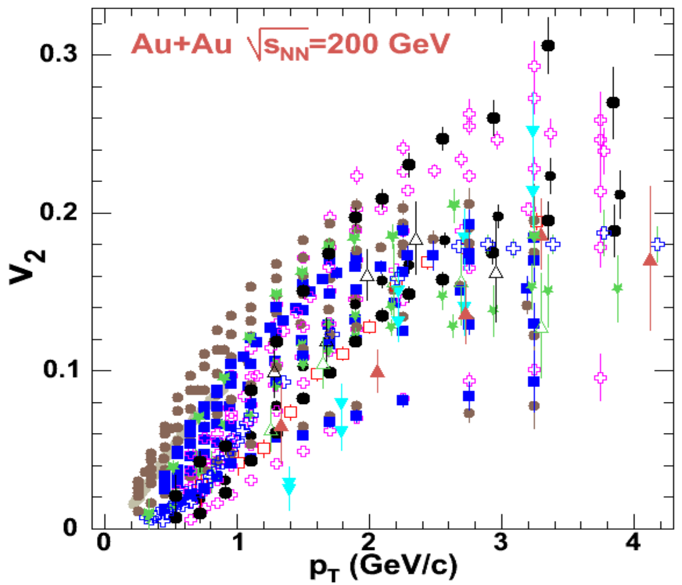
The general features of the collective flow could, in principle, be expressed in terms of scale-invariant quantities. In this way the particular differences arising from the different initial conditions, masses, energies, etc. , can be separated from the general fluid-dynamical features

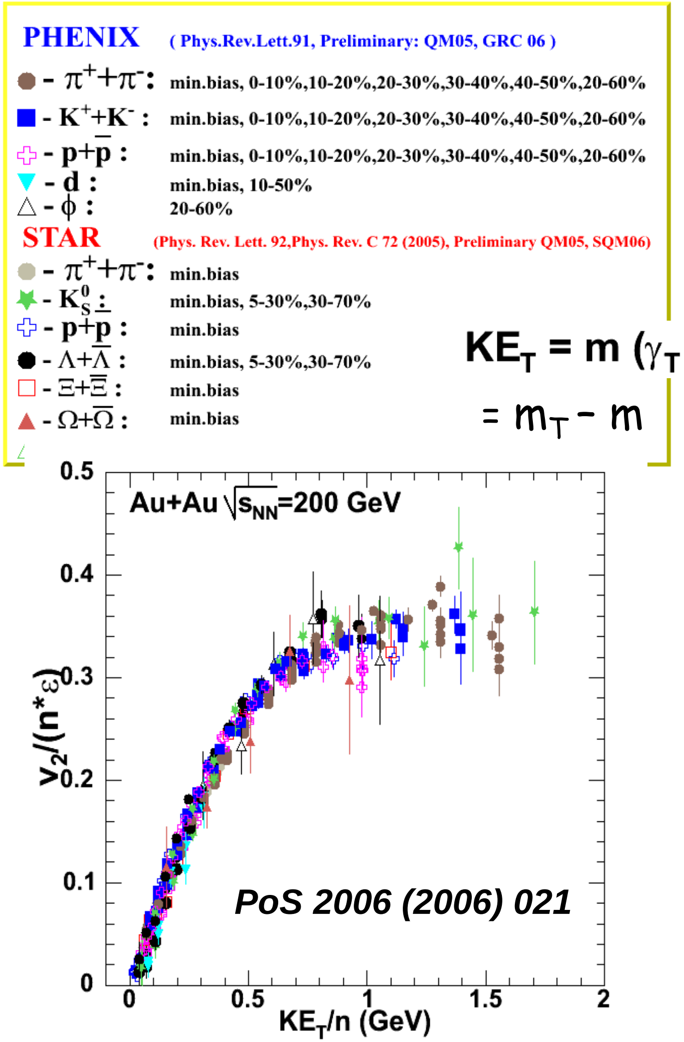
"Collective flow in heavy-ion collisions", W. Reisdorf, H.G. Ritter Ann.Rev. Nucl.Part.Sci. 47 (1997) 663-709 :

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.

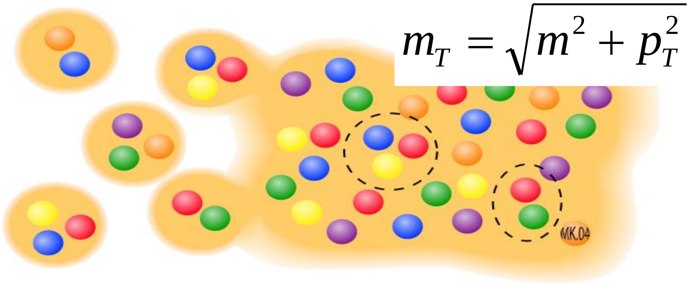
The proposal to look for scaling relations and use them – is very old !!!!

Anisotropic Flow at RHIC – scaling relations





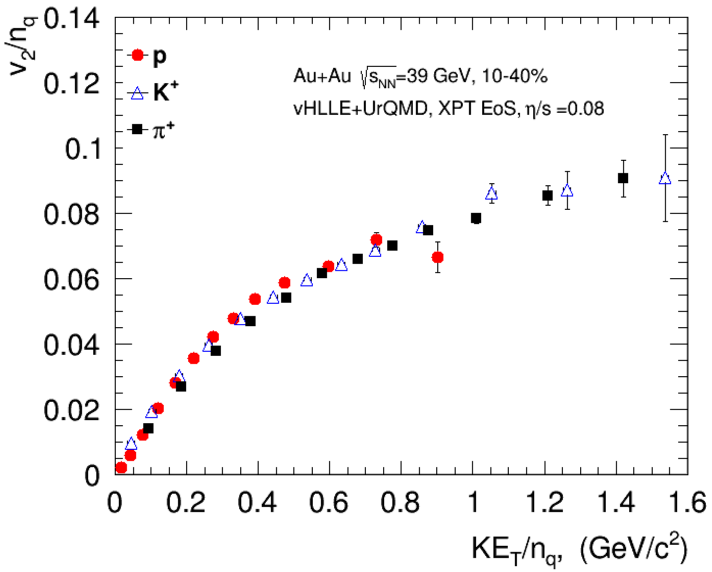
$$KE_T = m(\gamma_T - 1)$$
$$= m_T - m$$

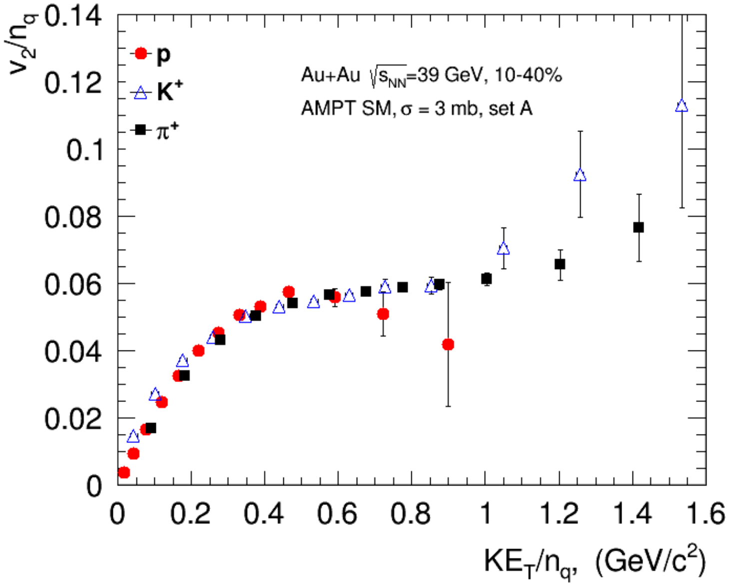


$$m_T = \sqrt{m^2 + p_T^2}$$

n=2 for mesons and n=3 for baryons

KE_T / n_q scaling : hybrid models





UrQMD + 3D viscous hydro model vHLLE + UrQMD

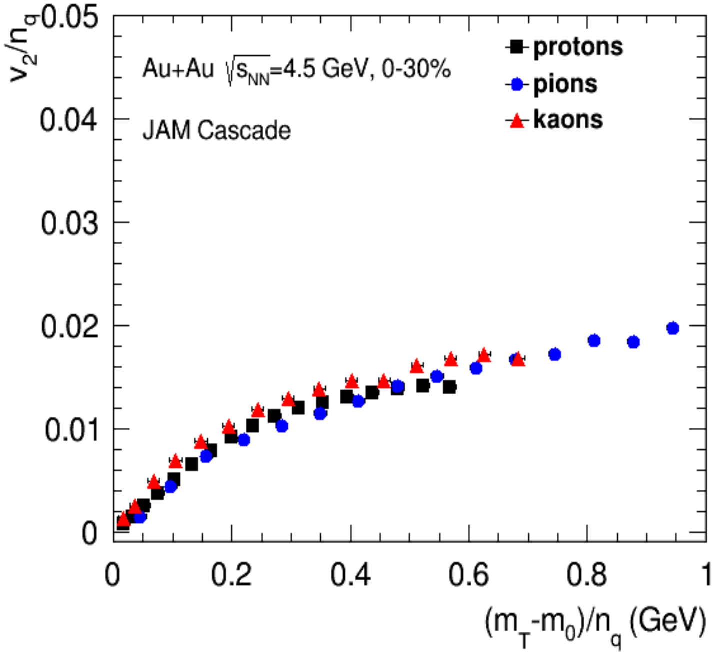
Iurii Karpenko, Comput. Phys. Commun. 185 (2014), 3016
https://github.com/yukarpenko/vhlle

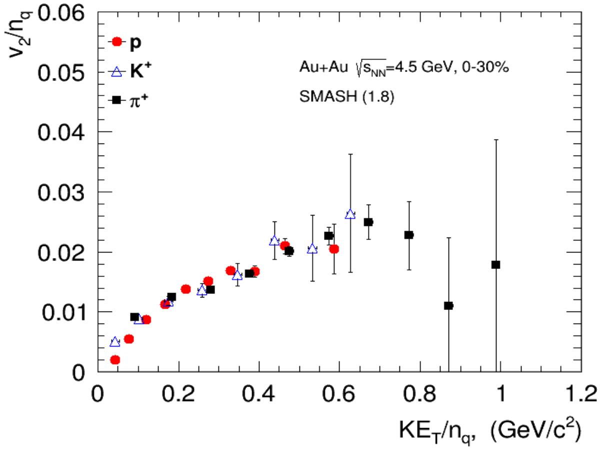
Initial conditions: model UrQMD
QGP phase: 3D viscous hydro (vHLLE) EOS (XPT)
Hadronic phase: model UrQMD

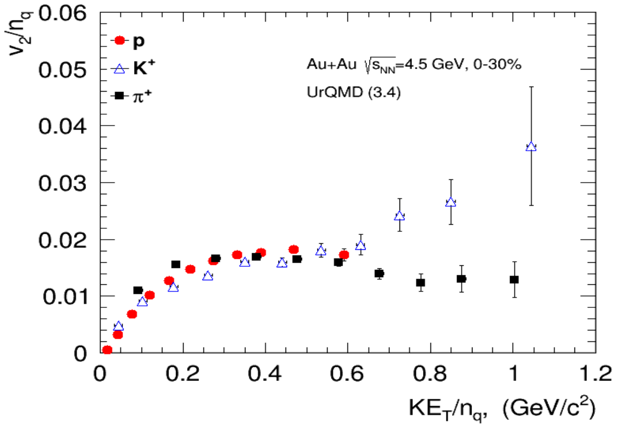
A Multi-Phase Transport model (AMPT) for high-energy nuclear collisions. (v1.26t9b/v2.26t9b)
Initial conditions: model HIJING
QGP phase: Zhang's parton cascade for modeling partonic scatterings
Hadronic phase: model ART

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

KE_T / n_q scaling : UrQMD / SMASH / JAM model



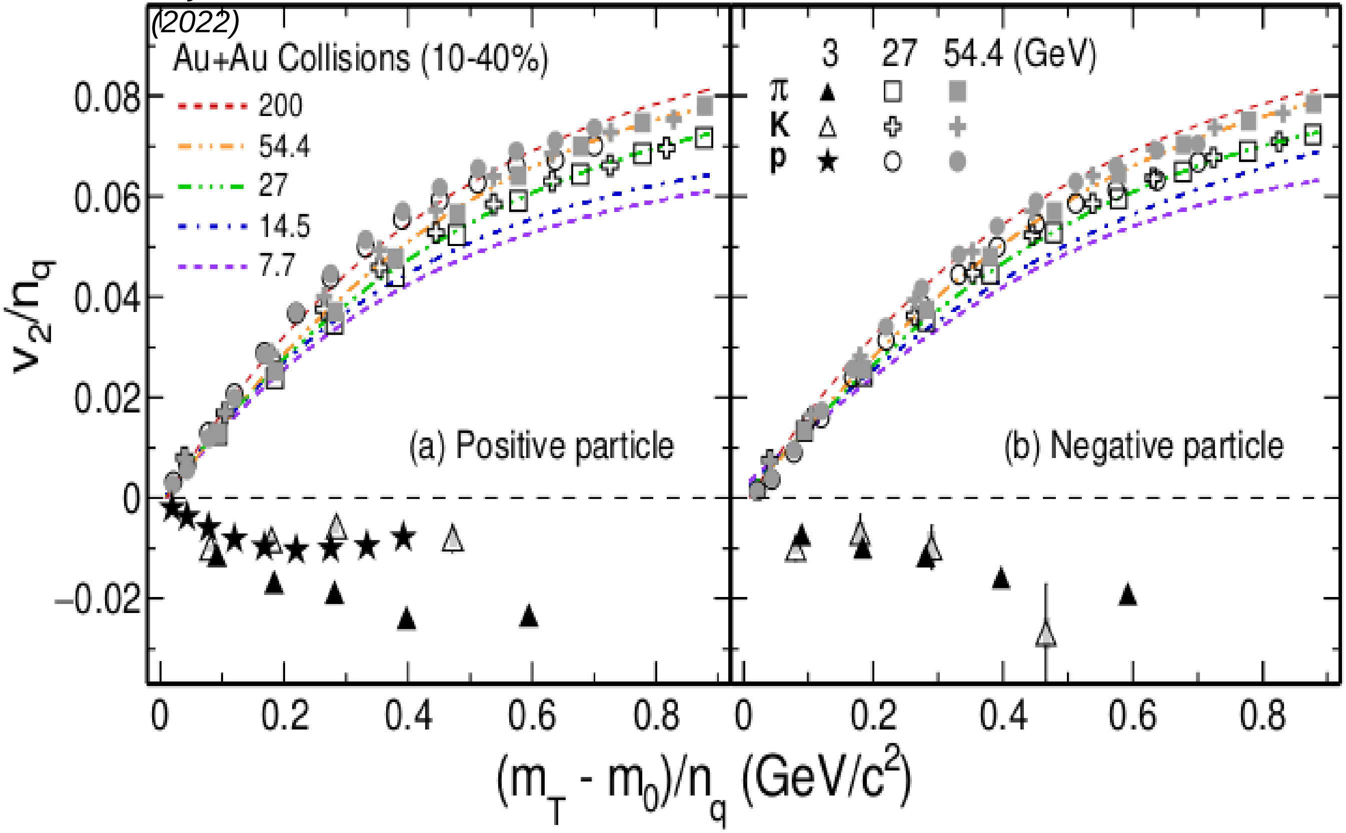




Pure String/Hadronic Cascade models give v_2 signals – which follow scaling

Dissapearence of partonic collectivity in $\sqrt{s_{NN}} = 3$ GeV Au+Au collisions at RHIC

Phys. Lett. B 827, 137003 (2022)

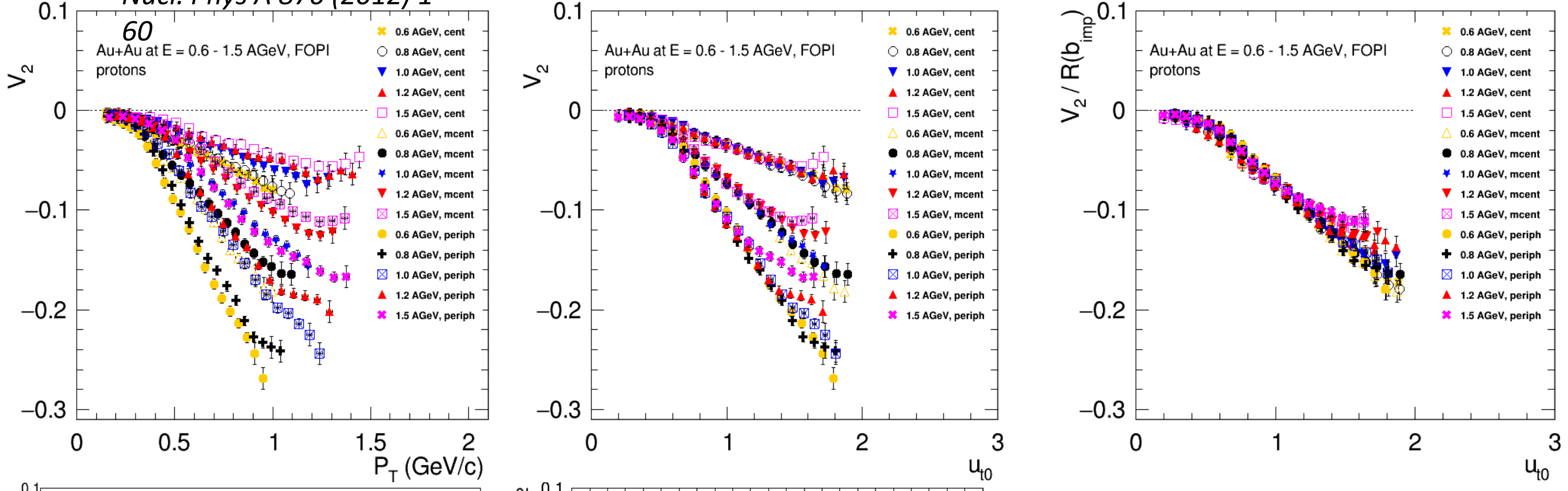


Breaking of NCQ scaling at 3 GeV

"imply the vanishing of partonic collectivity and a new EOS, likely dominated by baryonic interactions in the high baryon density region"

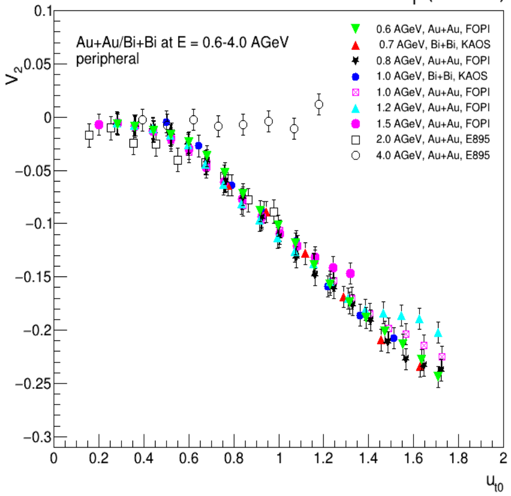
Scaling relations at SIS – scaling with passage time

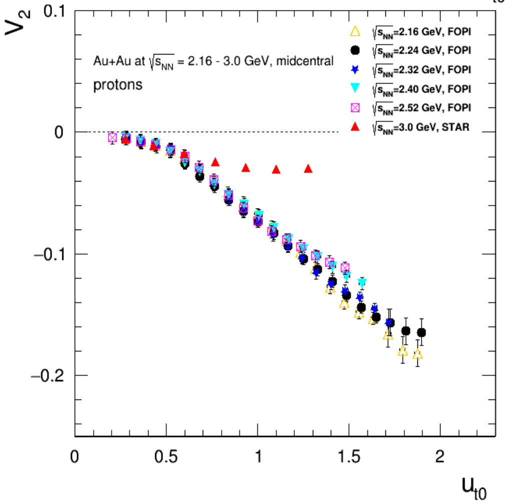
Nucl. Phys A 876 (2012) 1-60



$$u_{t0} = \frac{p_T}{m_0 \beta_{CM} \gamma_{CM}} \equiv \frac{p_T t_{pass}}{2 R m_0}$$

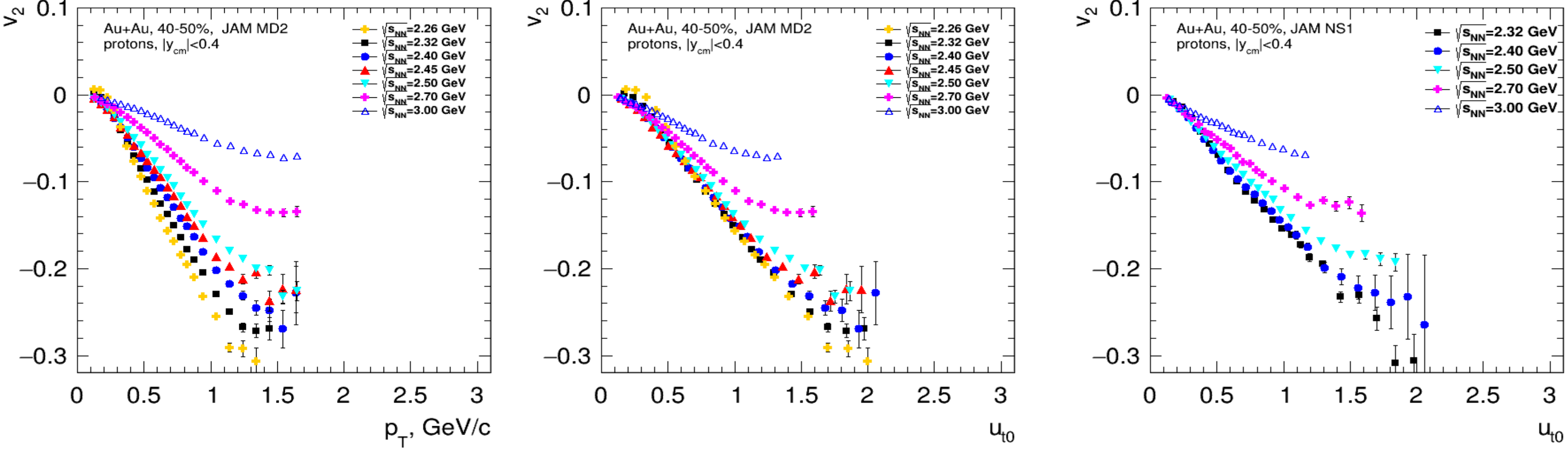
$$t_{pass} = \frac{2R}{\beta_{CM} \gamma_{CM}}$$

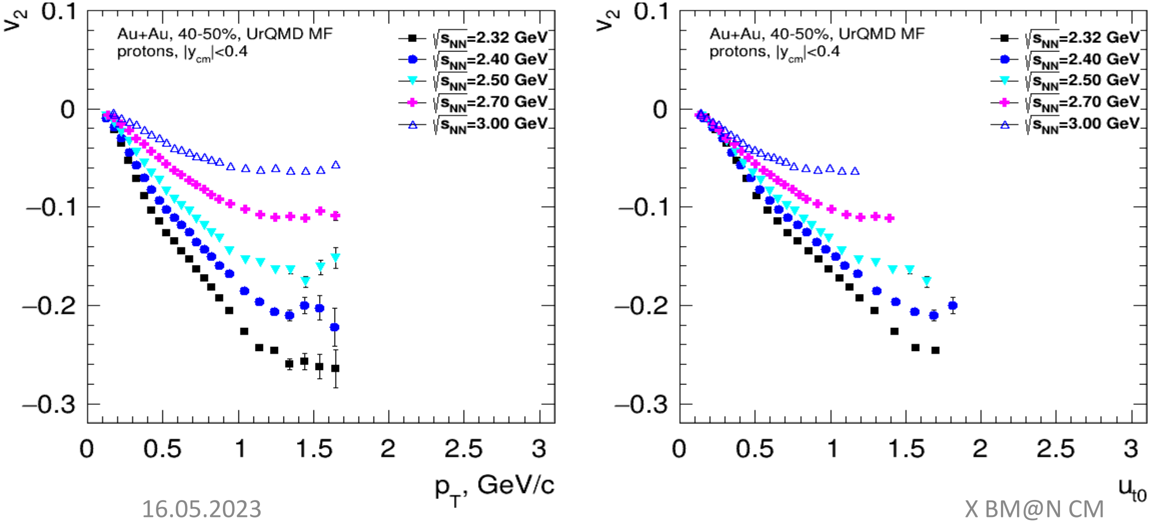




- The rather good scaling observed suggests that c_s does not change significantly over beam energy range $E_{kin} = 0.4 - 2$ AGeV ($\sqrt{s_{NN}} = 2 - 2.7$ GeV)
- Scaling breaks at $E_{kin} = 2.9$ AGeV ($\sqrt{s_{NN}} = 3$ GeV)

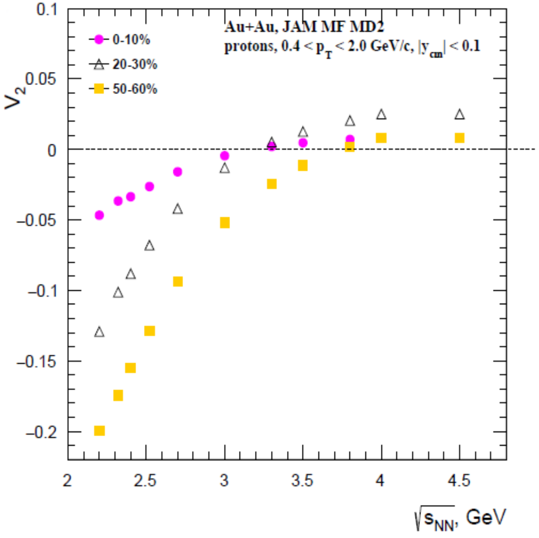
u_{t0} scaling: mean-field models

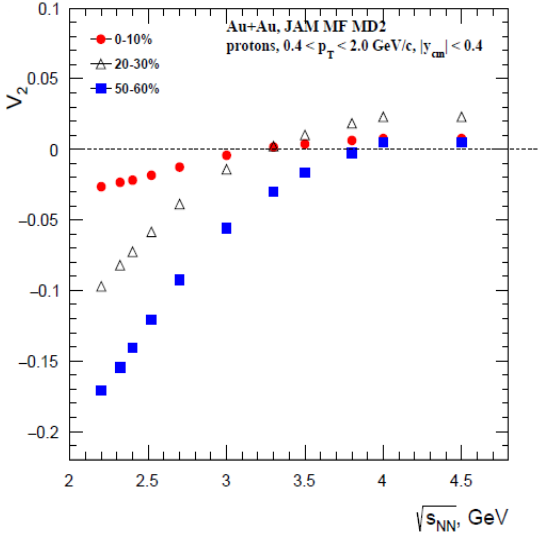




- Scaling holds for both JAM and UrQMD models with mean-field potentials for all EOS
- Similar trend with experimental data: scaling breaks at around $\sqrt{s_{NN}} \geq 2.7$ GeV
- Scaling can provide additional constraints for models

$v_2(y)$ transition from out-of-plane to in-plane



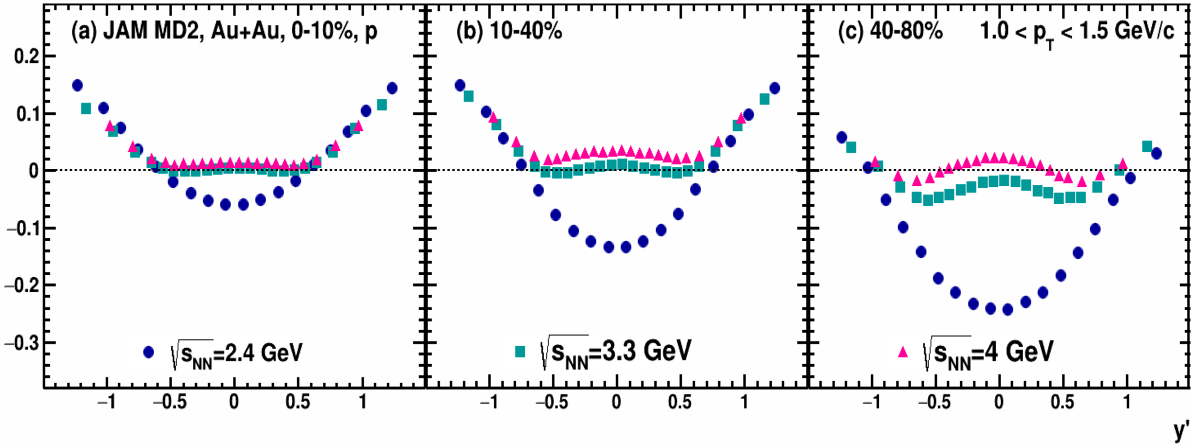


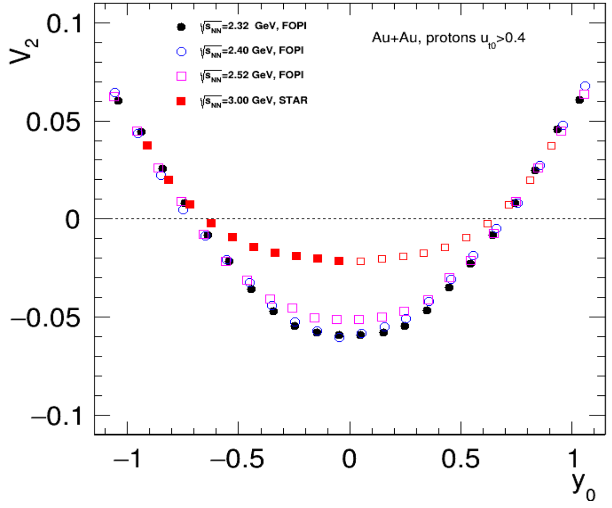
P. Parfenov, Particles 5, no.4, 561-579 (2022)

Transition of v_2 from out-of-plane to in-plane can be a good tool to constrain models and extract information about EOS

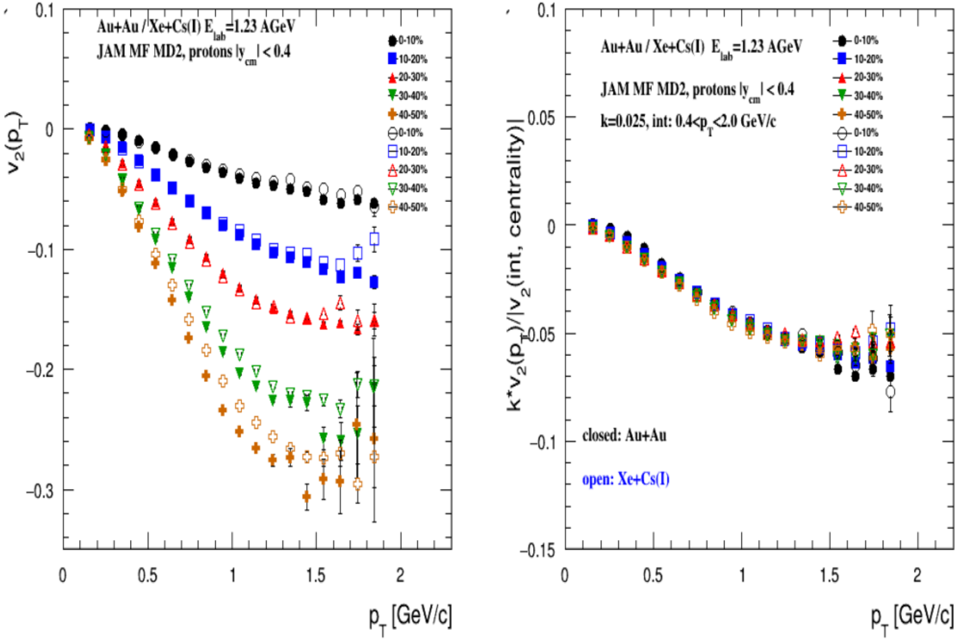
- $v_2 \approx 0$ in midrapirity at $\sqrt{s_{NN}}$=3.3 GeV for central and mid-central collisions
- $v_2 < 0$ for peripheral collisions

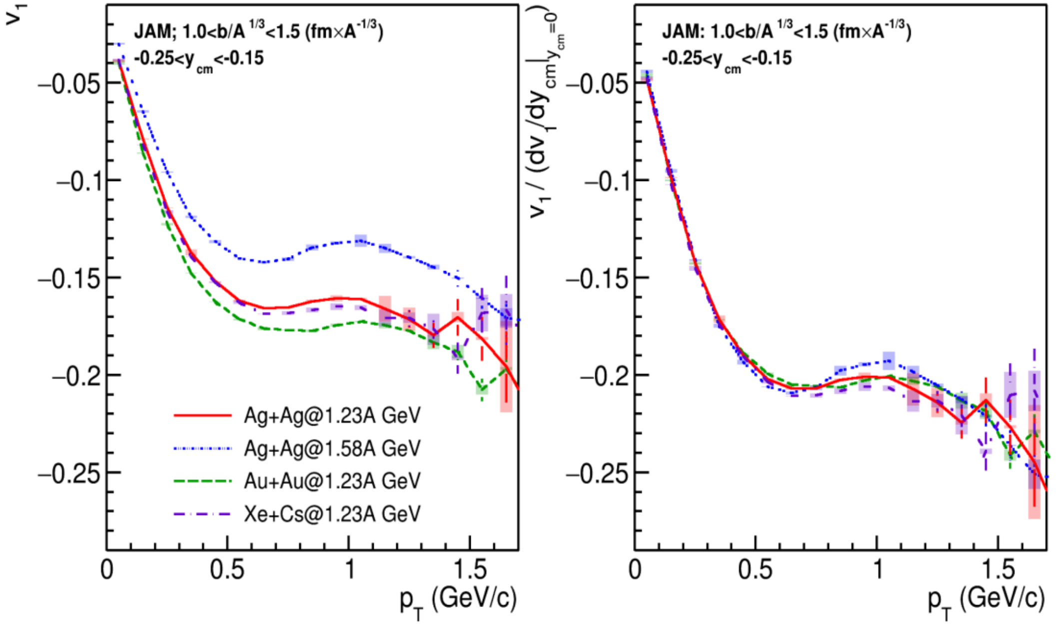
Transition from out-of-plane to in-plane depends on centrality and rapidity

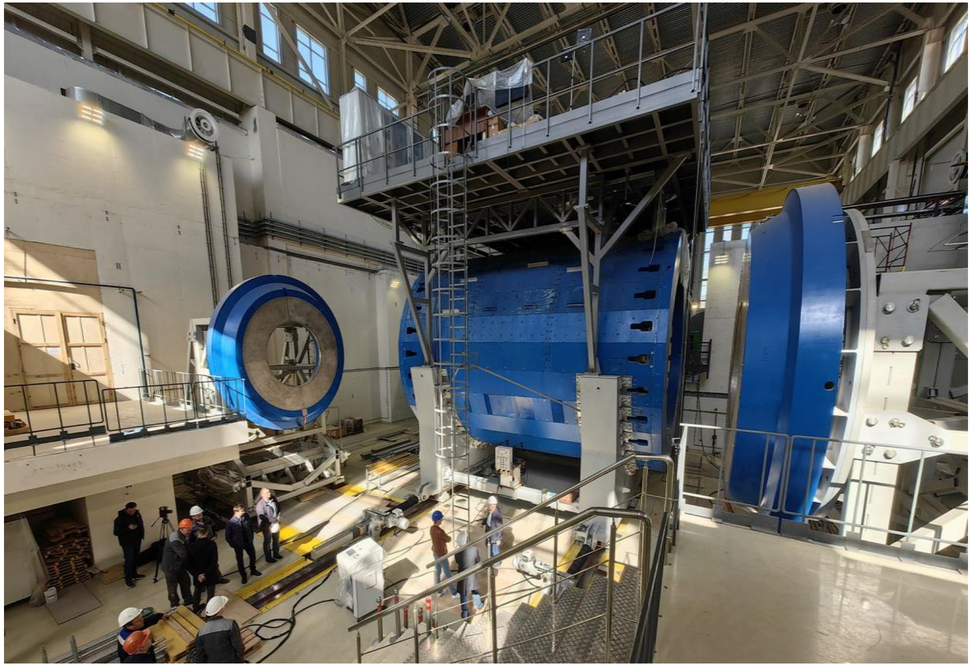




System size dependence of anisotropic flow

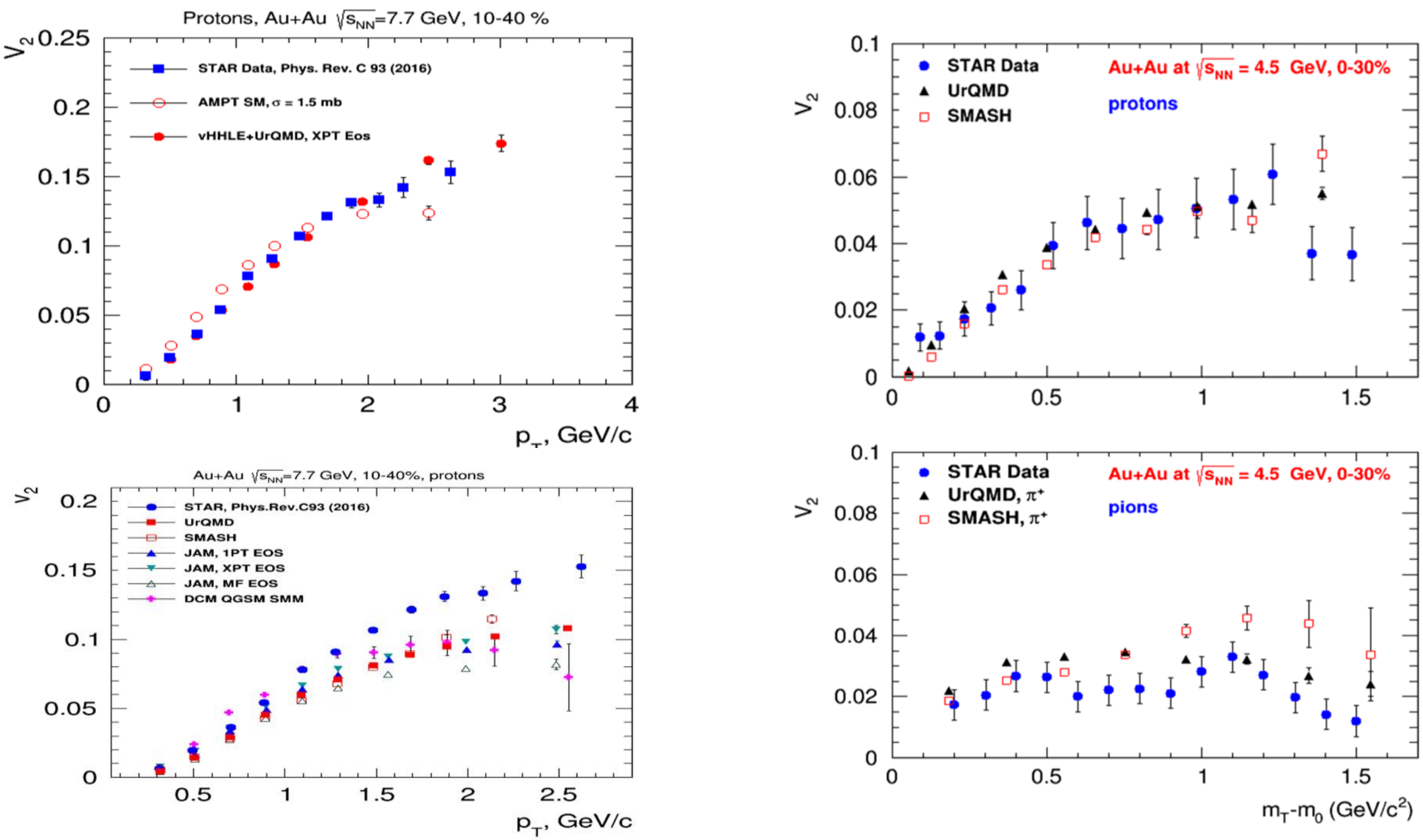






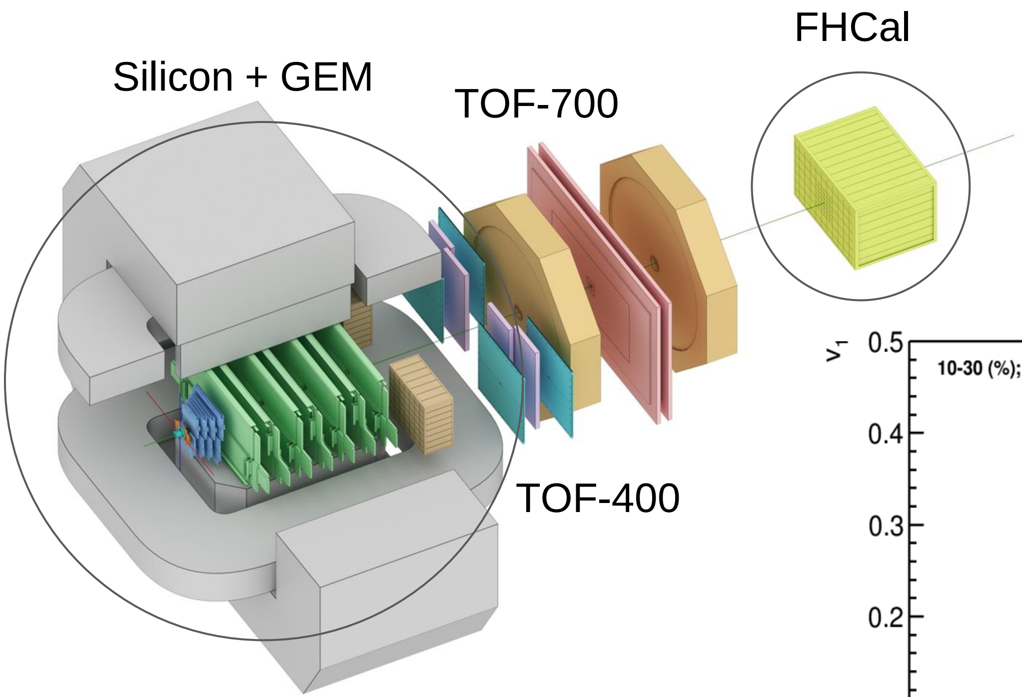
- ❖ **The NICA project is approaching its full commissioning:**
  - ✓ already running in the fixed-target mode – BM@N since 2018
  - ✓ start of operation in collider mode in 2025 – MPD
- ❖ Collision system available with the current sources: C (A=12), N (A=14), Ar (A=40), Fe (A=56), Kr (A=78-86),
  Xe (A=124-134), Bi (A=209)

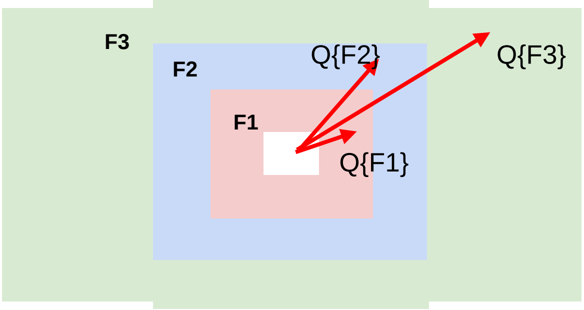
Elliptic Flow (v_2) at NICA energies: Models vs Data

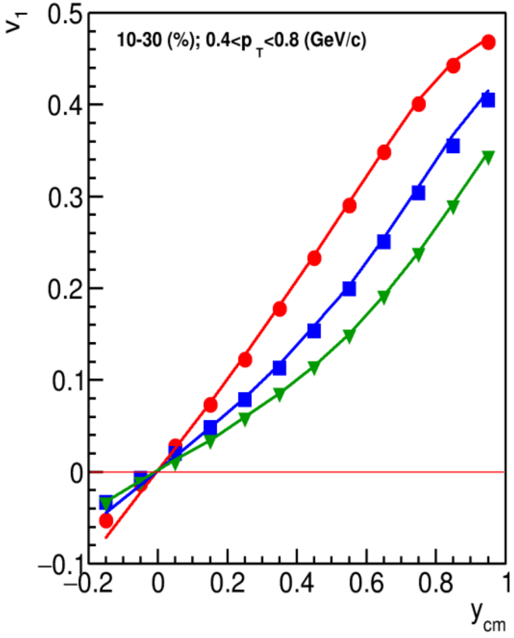


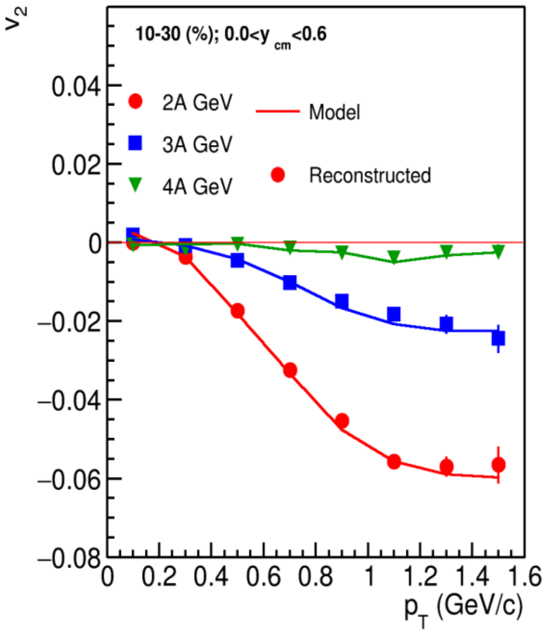
at $\sqrt{s_{NN}} \geq$ 7.7 GeV pure string/hadronic cascade models underestimate v_2 – need hybrid models with QGP phase (vHLLE+UrQMD, AMPT with string melting,…) at $\sqrt{s_{NN}} \geq$ 3-4.5 GeV pure hadronic models give similar v_2 signal compared to STAR data

The BM@N experiment (GEANT4 simulations for Xe+Cs(I) run)



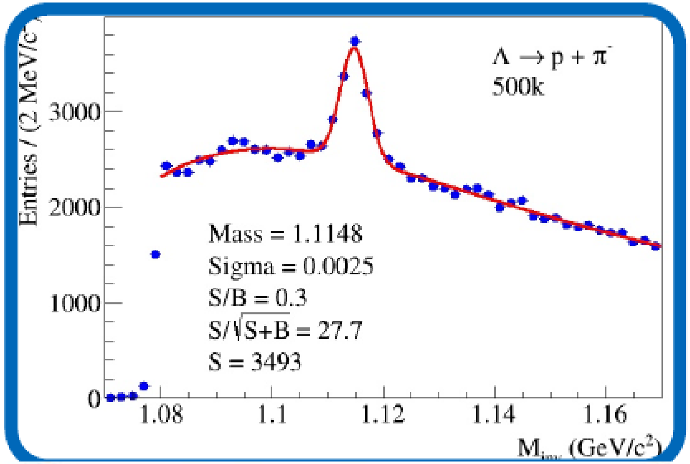


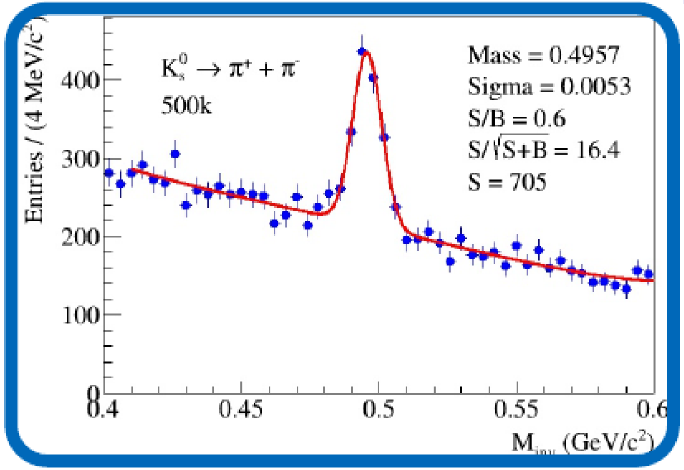


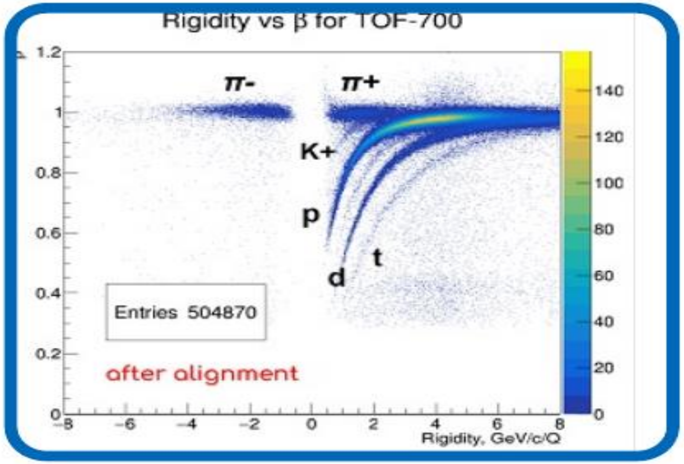


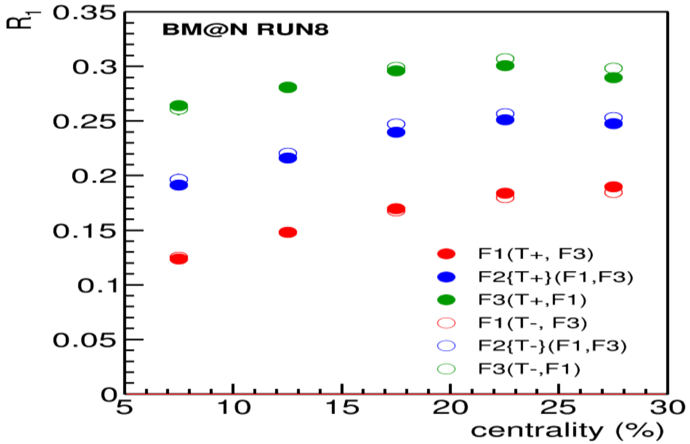
Good agreement between reconstructed directed and elliptic flow of protons and pure model data

BM@N (Baryonic Matter @ Nuclotron)









December 2022 – February 2023: first physics run with Xe+Cs(I) (3.0 AGeV (50 M events) и 3.4 AGeV (500 M events))

Back-up slides

Summary and outlook

Measurements of anisotropic flow, flow fluctuations, correlations

between flow of different harmonics are sensitive to many details of the initial conditions

and the system evolution. It may provides access to the transport properties of the medium: EOS, sound speed (cs), viscosity, etc.

Scaling relations may help to understand the physics of the process

The multi-differential high-statistics data from STAR/HADES/BM@N should

enable a direct extraction of the EOS parameters at high baryon density

via a Bayesian fit of the models to the data.

Back-up slides

Ultimately, the
multi-differential high-statistics data presented here should
enable a direct extraction of the EOS parameters via a
Bayesian fit of the models to the data.

OUTLINE

1. Flow and sQGP at RHIC/LHC
2. Scaling properties of anisotropic flow
3. Flow results from Beam Energy Scans
4. Outlook for flow measurements at NICA