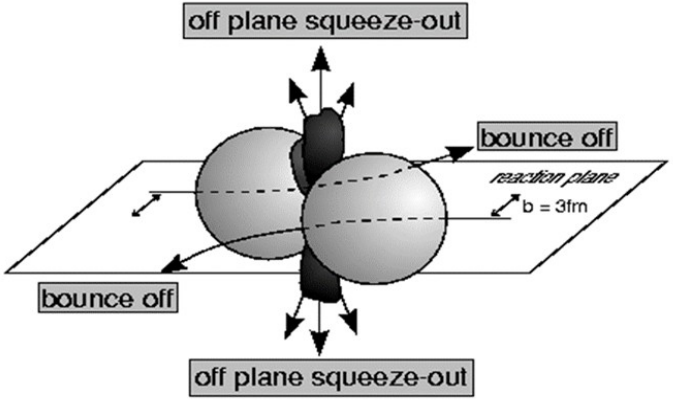
Измерения анизотропных коллективных потоков от LHC до NICA

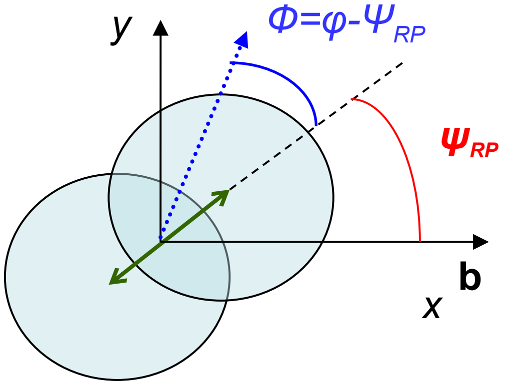
Аркадий Тараненко (НИЯУ МИФИ, ЛФВЭ ОИЯИ)

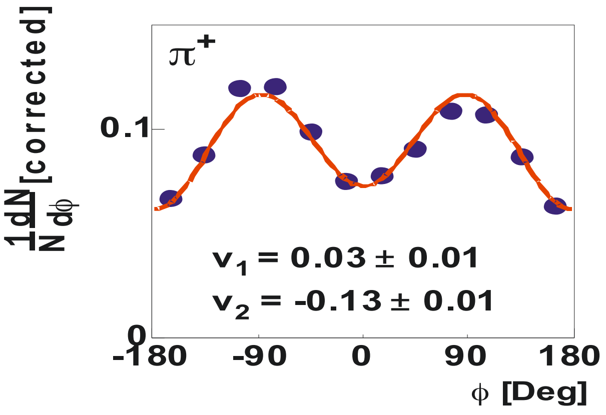


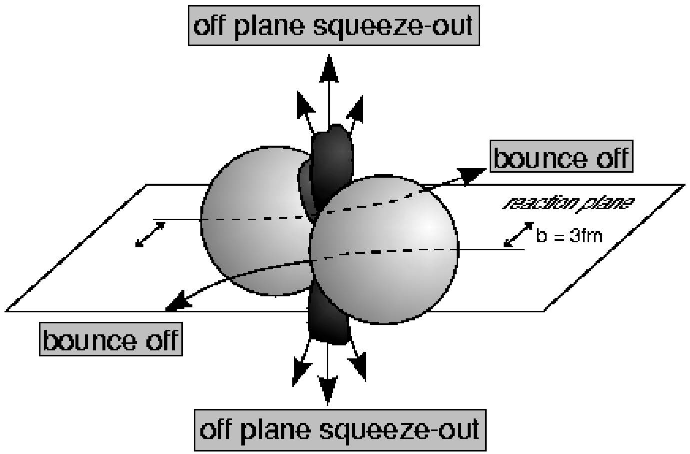
Научная сессия секции ядерной физики ОФН РАН, посвященная 300-летию Российской Академии Наук, ОИЯИ, 1-5 апреля 2024

Работа поддержана Министерством науки и высшего образования РФ, проект "Новые явления в физике элементарных частиц и ранней Вселенной" № FSWU-2023-0073

Azimuthal anisotropy of particles at HIC 1989-2024







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

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

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

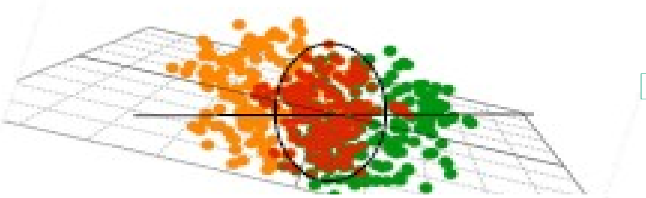
$$v_n = \langle \cos[n(\varphi - \Psi_{RP})] \rangle$$

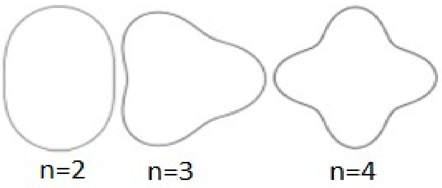
- Fourier coefficients v_n quantify anisotropic flow:

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



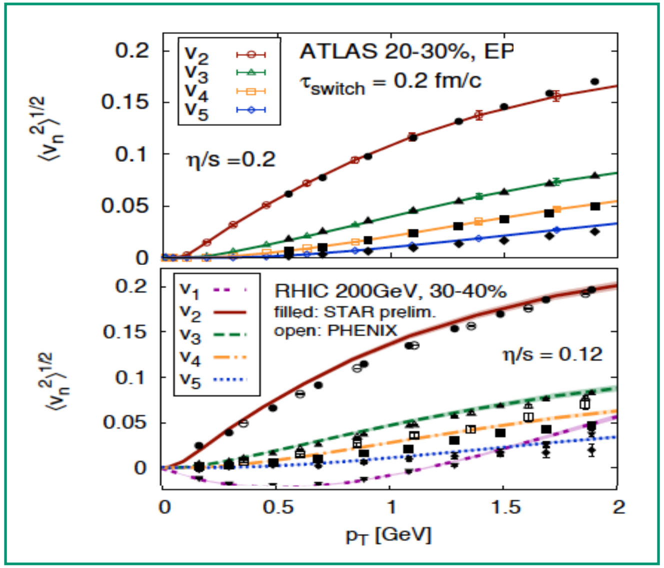


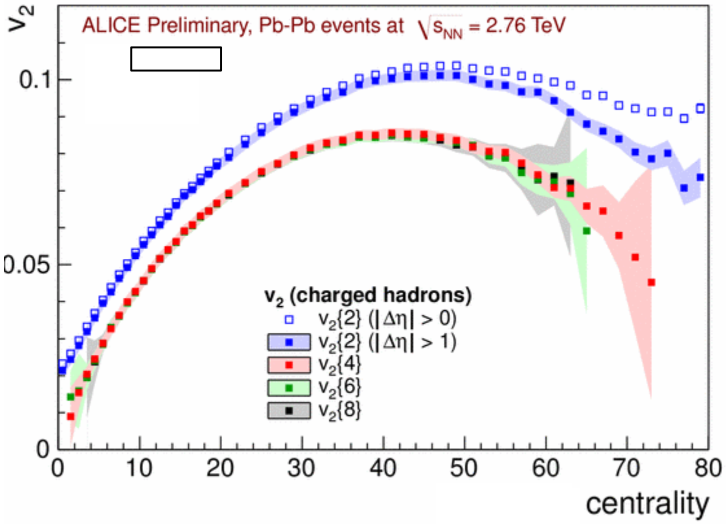
$$\epsilon_n = \sqrt{\frac{\langle r^n \cos n\phi\rangle + \langle r^n \sin n\phi\rangle}{\langle r^n\rangle}}$$

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

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



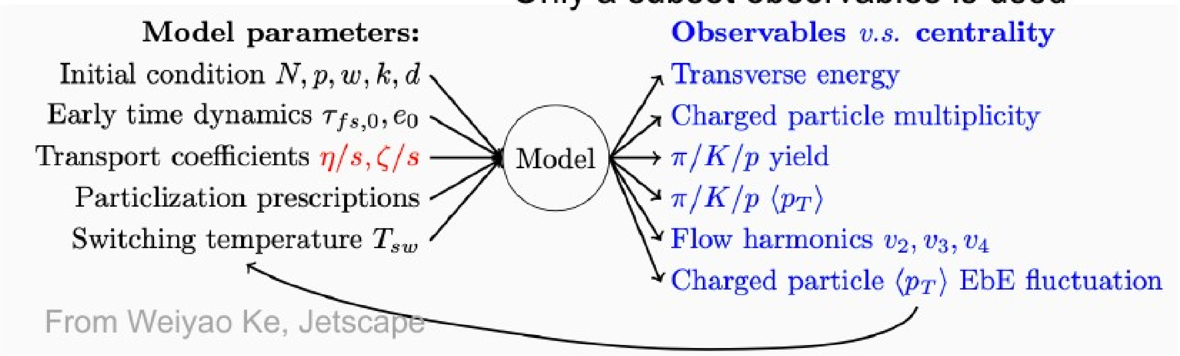


Flow and non-Flow, Fluctuations

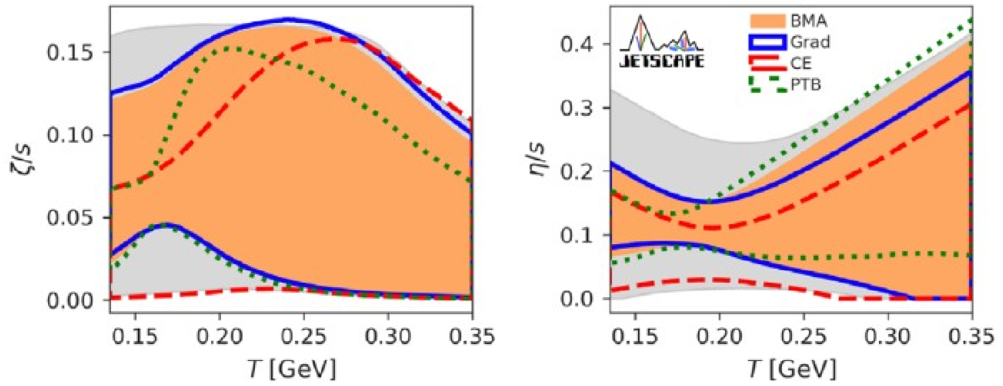
State-of-the-art modeling of HI collisions

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

Only a subset observables is used



- Detailed temperature dependence of viscosity!



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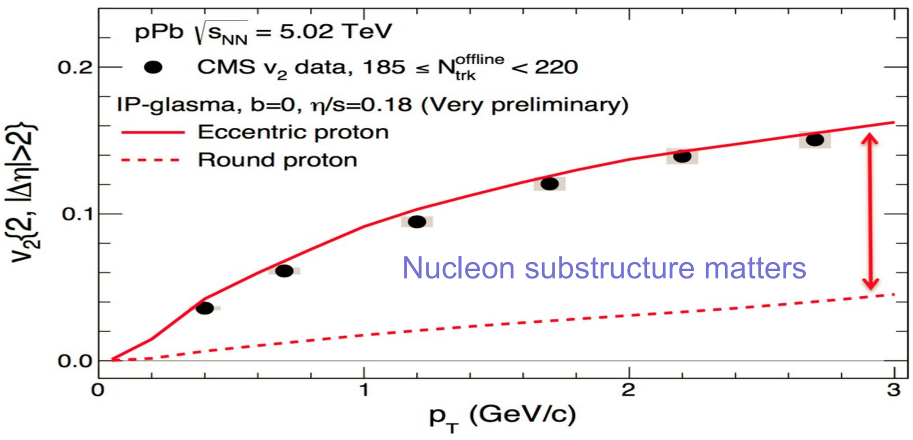
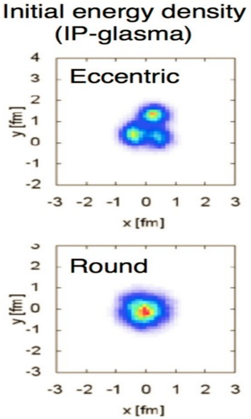
Trjactum PRL.126.202301

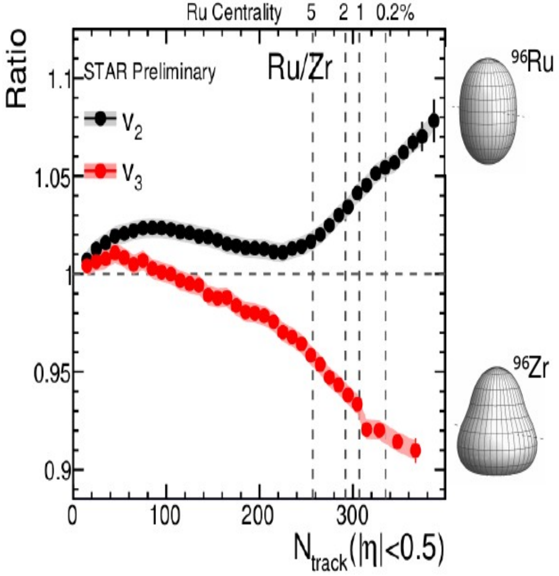
Major uncertainty: initial condition and pre-hydro phase

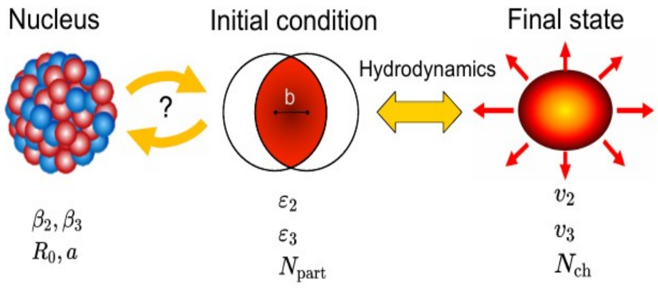
2011-2020





2020-2024





Anisotropic Flow at RHIC/LHC is acoustic

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 $\left(\frac{\eta}{s}, \frac{\zeta}{s}, \ldots\right)$.

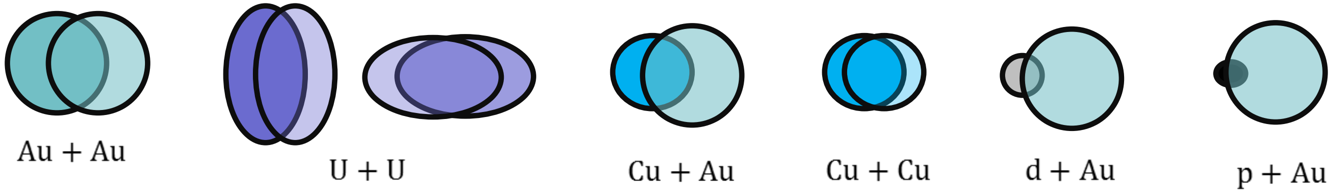
arXiv:1305.3341
Roy A. Lacey, et al.

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

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

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

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

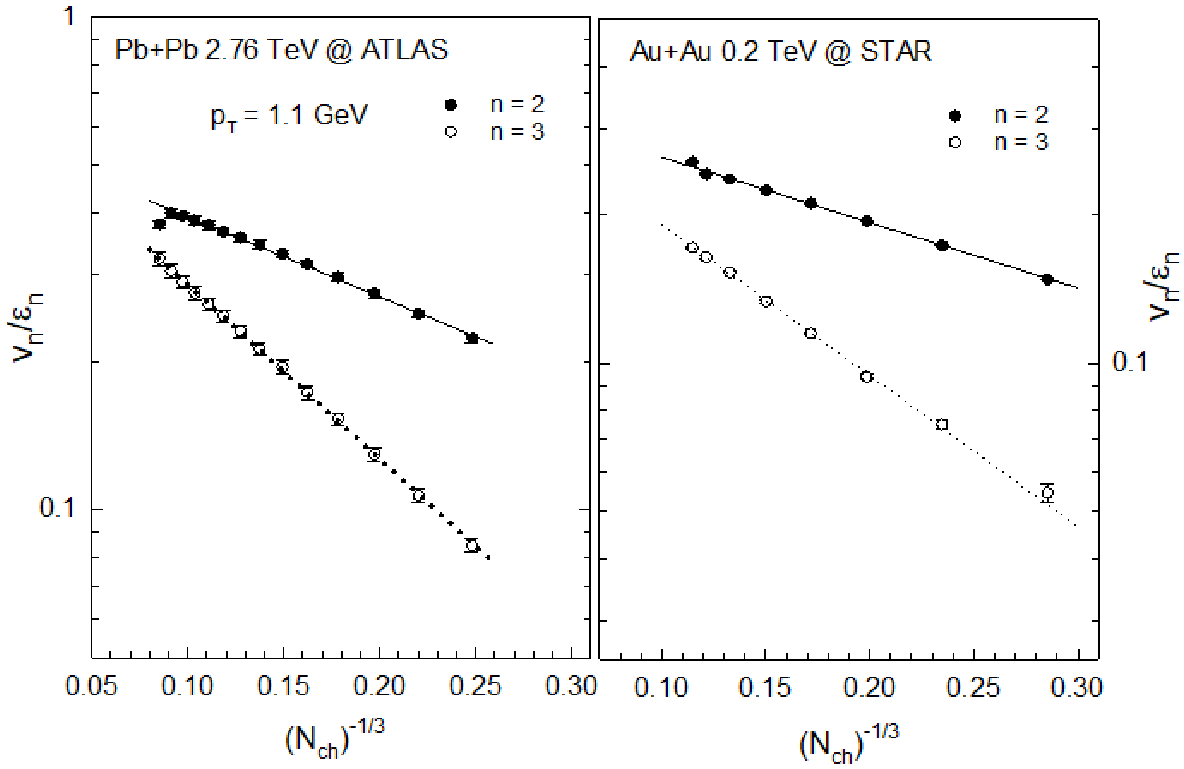


Scaling expected For *similar* $\frac{\eta}{s}$ *and* $\frac{dN}{d\eta}$

Acoustic Scaling –

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

$$RT \propto \left(\frac{dN_{chg}}{d\eta}\right)^{1/3}$$



- ✓ **Characteristic 1/(RT) viscous damping validated**
  - ✓ **Clear pattern for n^2 dependence of viscous attenuation**
  - ✓ **Important constraint for η/s & ζ/s**

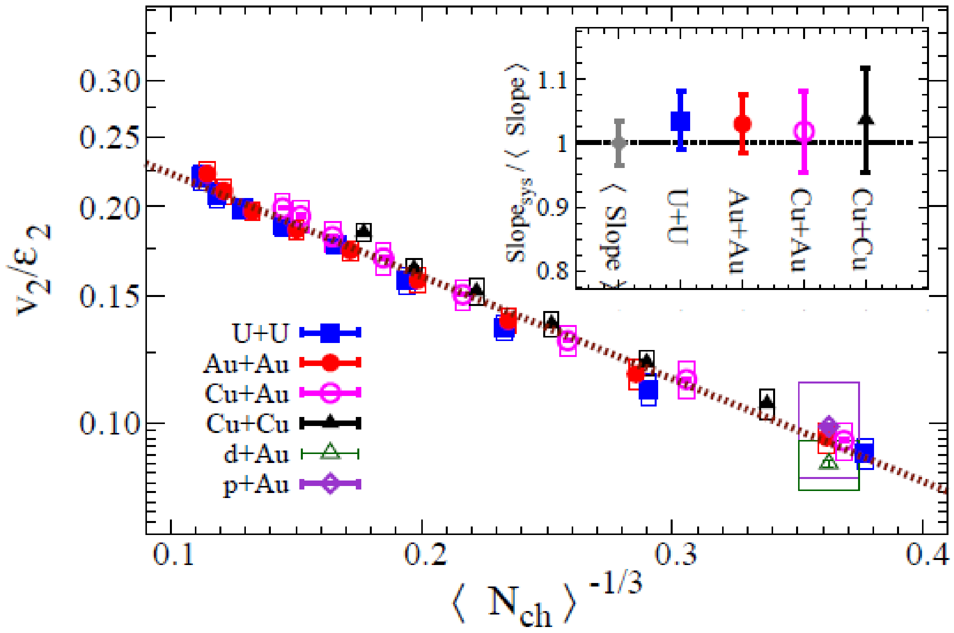
Flow is acoustic

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

$$\frac{v_n}{\varepsilon_n} \propto e^{-\beta n^2},$$

$$\beta \propto \left(\frac{4}{3}\frac{\eta}{s} + \frac{\xi}{s}\right)\frac{1}{RT}$$

$\langle N_{ch} \rangle$ *dependence of* $\frac{v_2}{\varepsilon_2}$ for several systems



- ✓ **Characteristic 1/(RT) viscous damping validated**
- ✓ **Viscous damping supersedes the influence of eccentricity for "small" systems**
  - ✓ **Similar slopes imply similar $\frac{\eta}{s}$.**

Beam energy dependence of V_n

- Anisotropic flow attenuation:

$$v_n \propto k\,\varepsilon_n, \qquad k = e^{-\beta n^2}$$

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

- From macroscopic entropy considerations:

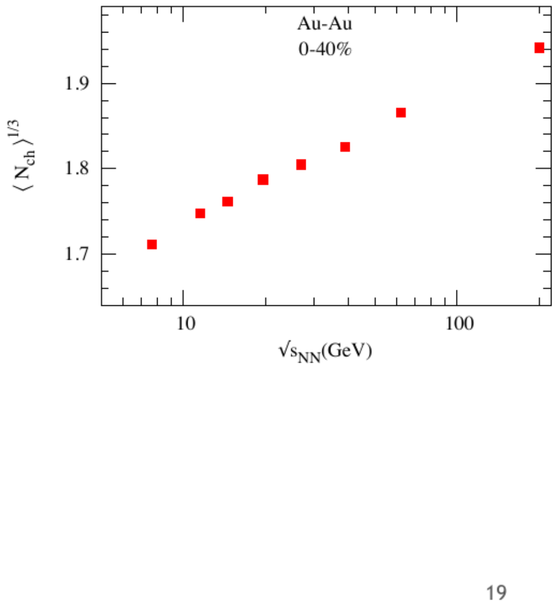
$$S \sim (RT)^3 \sim \langle N_{Ch}\rangle \text{ then } RT \sim \langle N_{Ch}\rangle^{1/3}$$

$$\ln\left(\frac{v_n}{\varepsilon_n}\right) \propto -\left(\frac{\eta}{s}\right)\langle N_{Ch}\rangle^{-1/3}$$

Using two different harmonics :

$$\left[\ln\left(\frac{v_n^{1/n}}{v_2^{1/2}}\right) + \ln\left(\frac{\varepsilon_2^{1/2}}{\varepsilon_n^{1/n}}\right)\right]\langle N_{Ch}\rangle^{1/3} \propto -A\left(\frac{\eta}{s}\right)$$

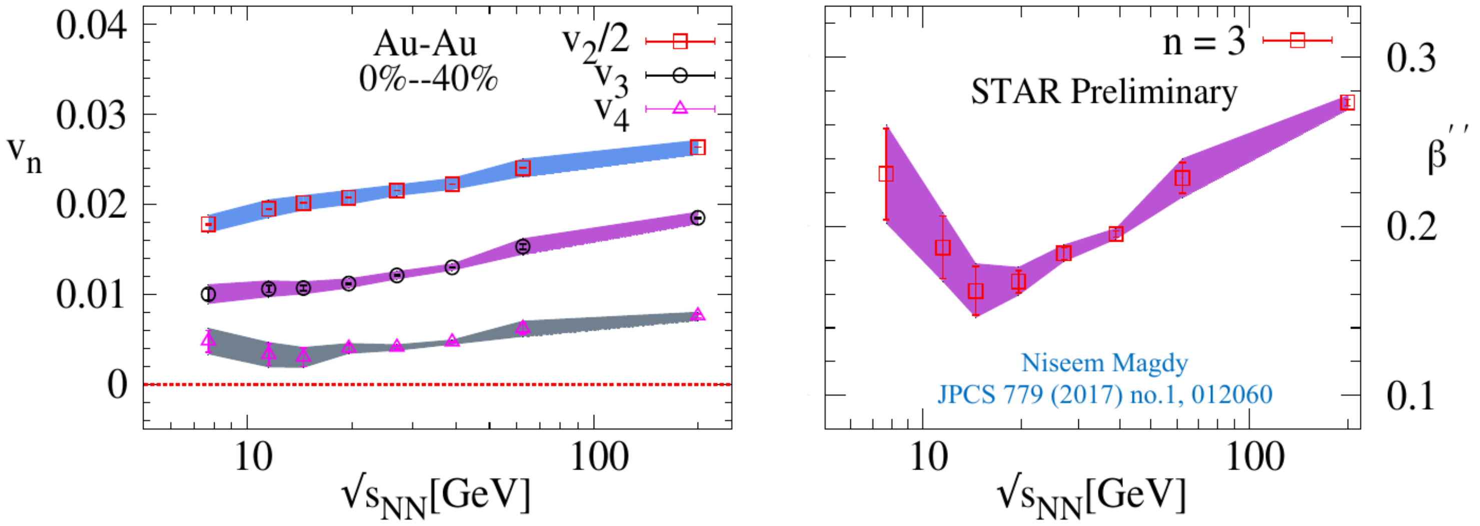
$$\beta'' = \ln\left(\frac{v_n^{1/n}}{v_2^{1/2}}\right)\langle N_{Ch}\rangle^{1/3} \propto -A\left(\frac{\eta}{s}\right)$$



Beam energy dependence of V_n

$$\beta'' = \ln\left(\frac{v_n^{1/n}}{v_2^{1/2}}\right)\langle N_{Ch}\rangle^{1/3} \propto -A\left(\frac{\eta}{s}\right)$$

A: is constant



V_n shows a monotonic increase with beam energy. The viscous coefficient, which encodes the transport coefficient ($\boldsymbol{\eta/s}$), indicates a non-monotonic behavior as a function of beam energy.

Anisotropic flow in Au+Au collisions at Nuclotron-NICA energies

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

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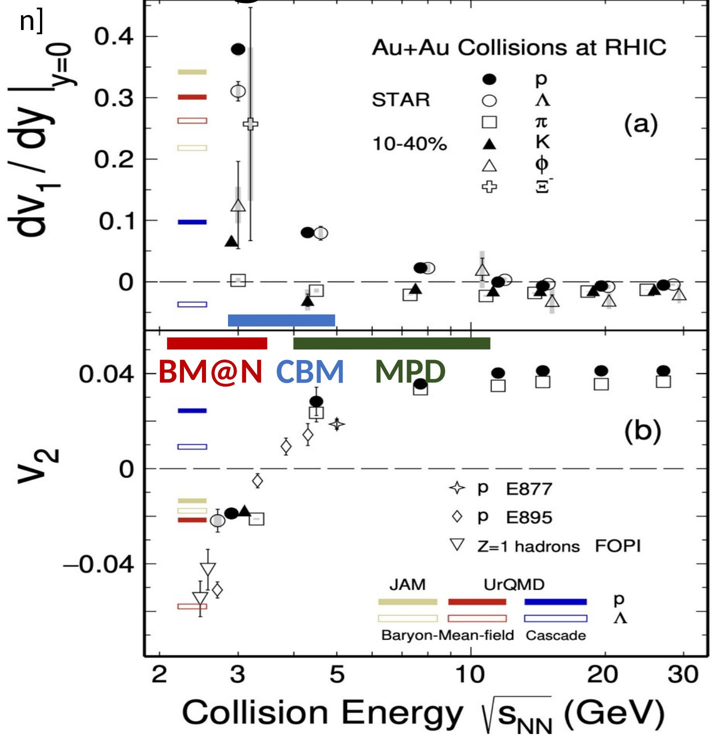
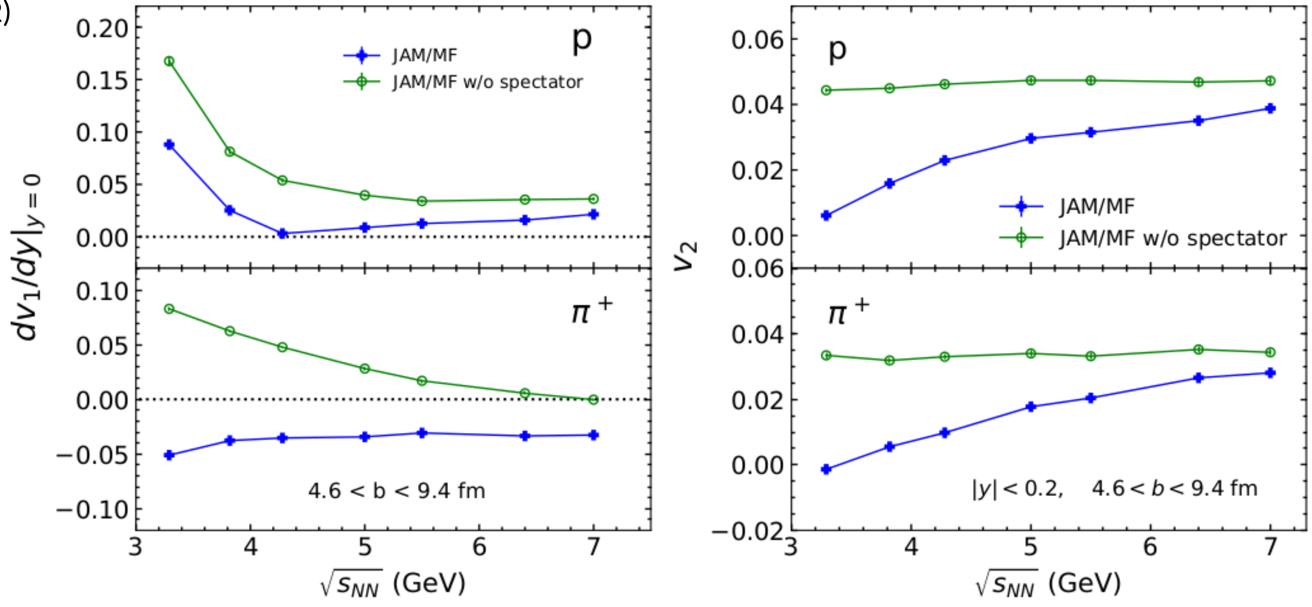




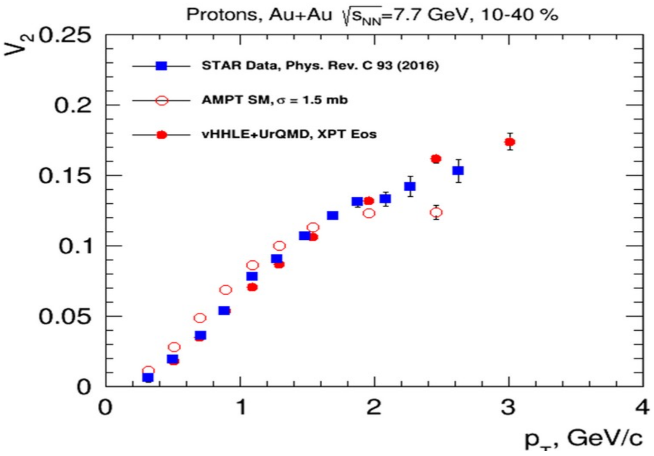
Phys. Rev. C 97, 064913 (2018)

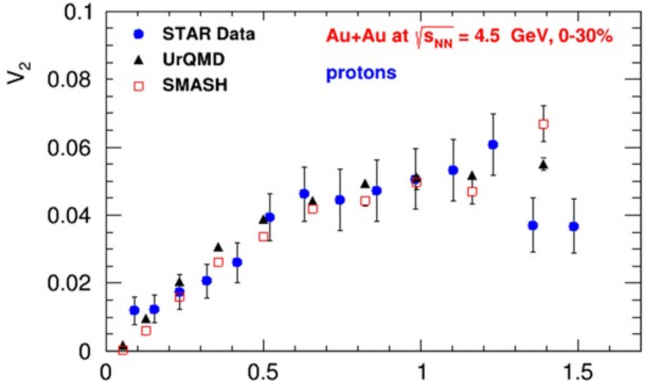
Anisotropic flow at FAIR/NICA energies is a delicate balance between:

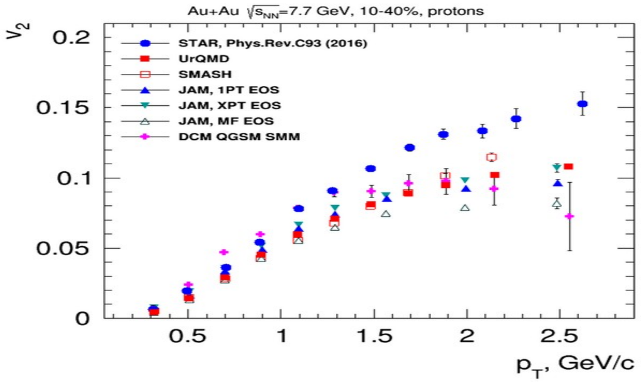
I. The ability of pressure developed early in the reaction zone () and

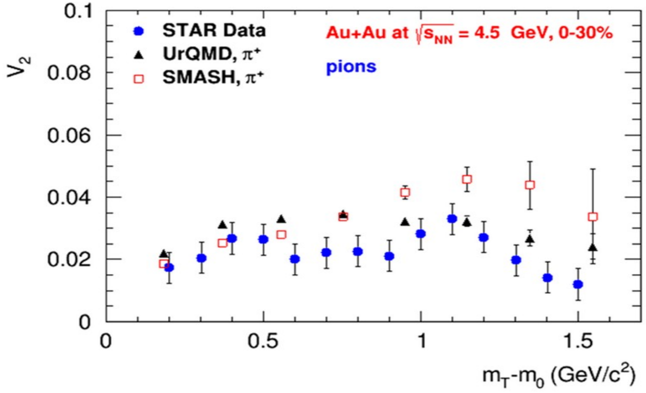
II. The passage time for removal of the shadowing by spectators ()

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



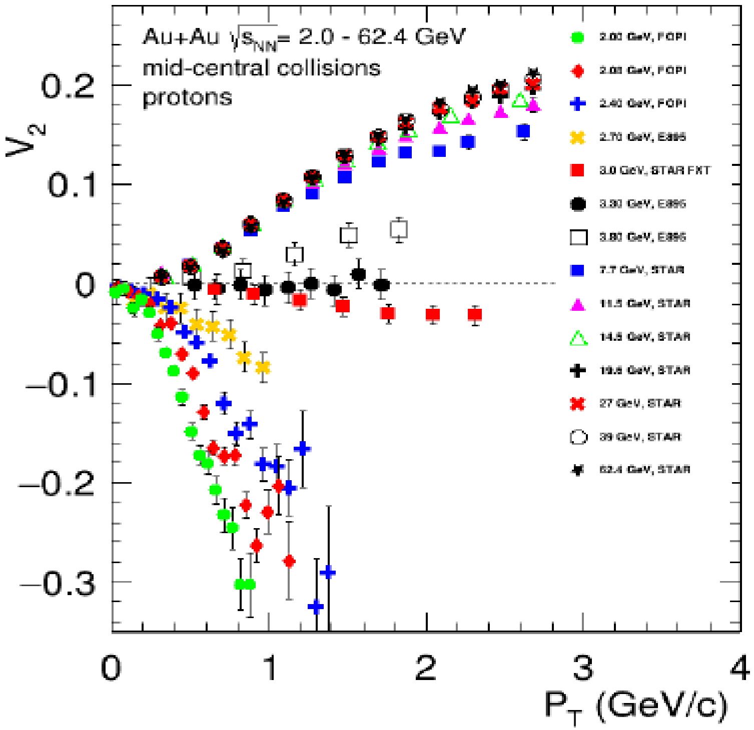


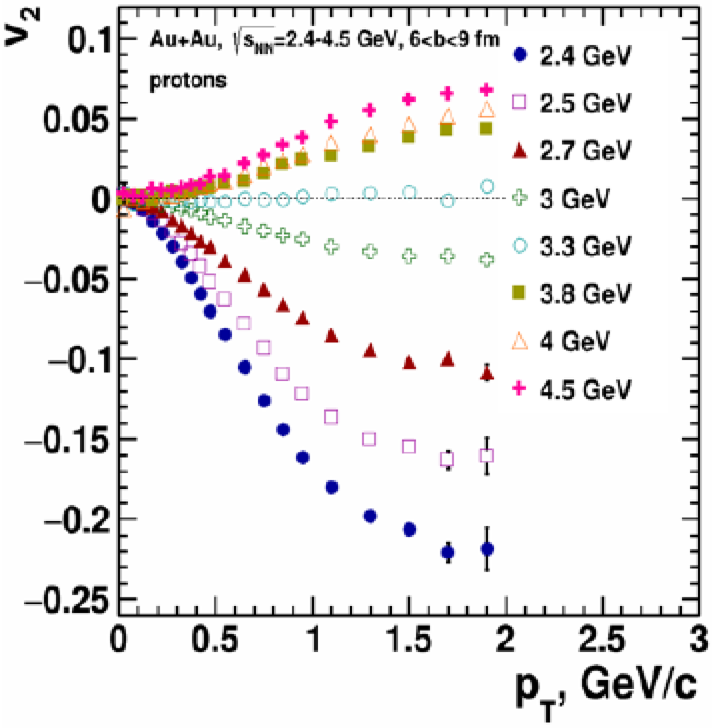




at $\sqrt{s_{NN}} \geq 7.7$ GeV pure string/hadronic cascade models underestimate v_2 – need hybrid models with QGP phase (vHLLE+UrQMD, AMPT with string melting,…) at $\sqrt{s_{NN}} \geq 3$-4.5 GeV pure hadronic models give similar v_2 signal compared to STAR data

Anisotropic flow in Au+Au collisions at Nuclotron-NICA energies





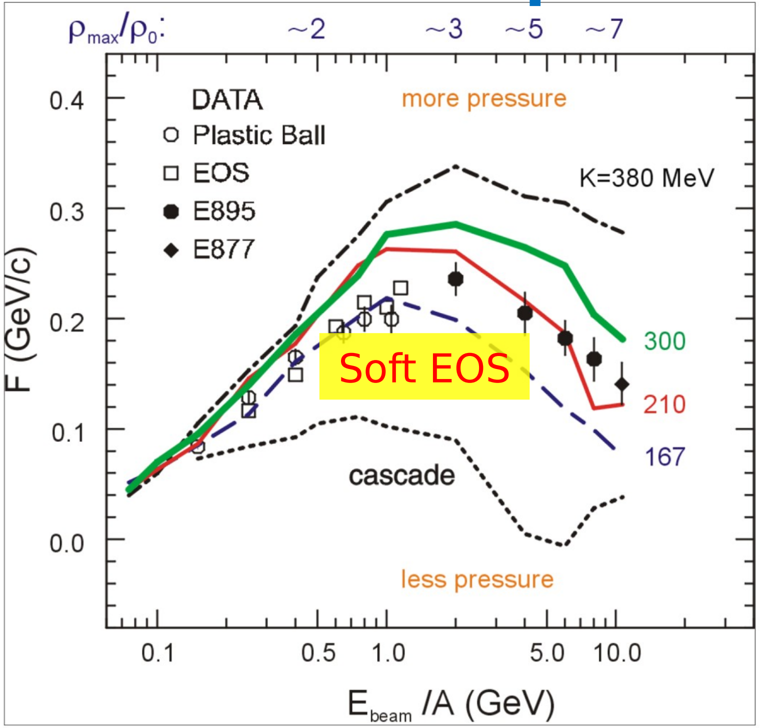
Anisotropic flow at FAIR/NICA energies is a delicate balance between:

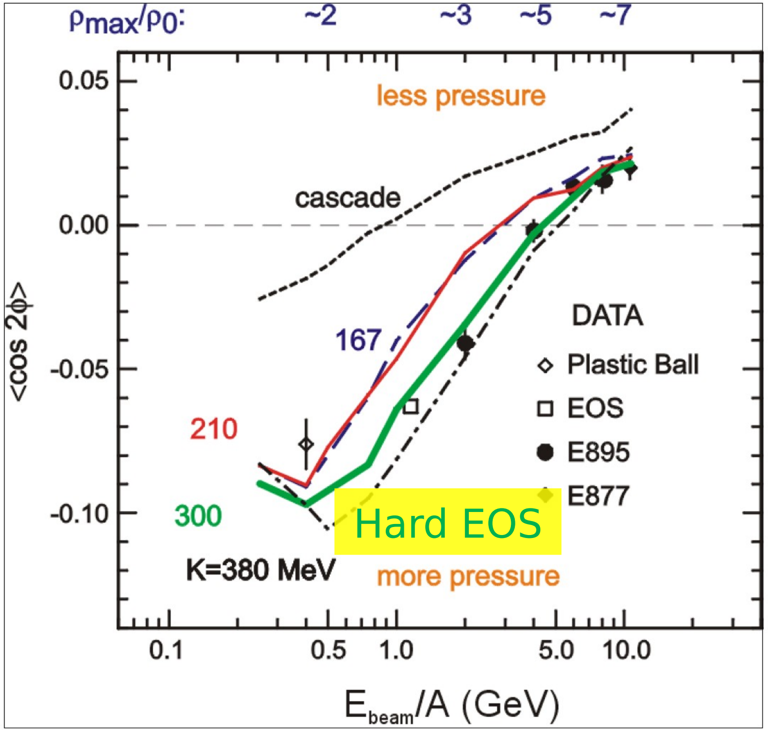
I. The ability of pressure developed early in the reaction zone () and

II. The passage time for removal of the shadowing by spectators ()

Nuclear incompressibility from collective proton flow

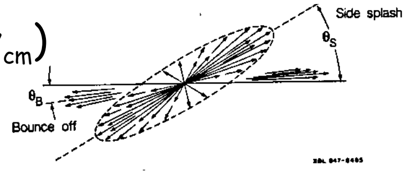
P. Danielewicz, R. Lacey, W.G. Lynch, Science 298 (2002) 1592



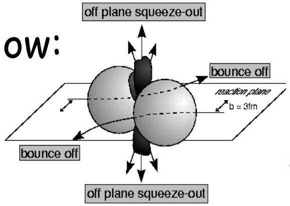


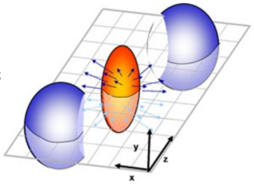
Transverse in-plane flow:

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



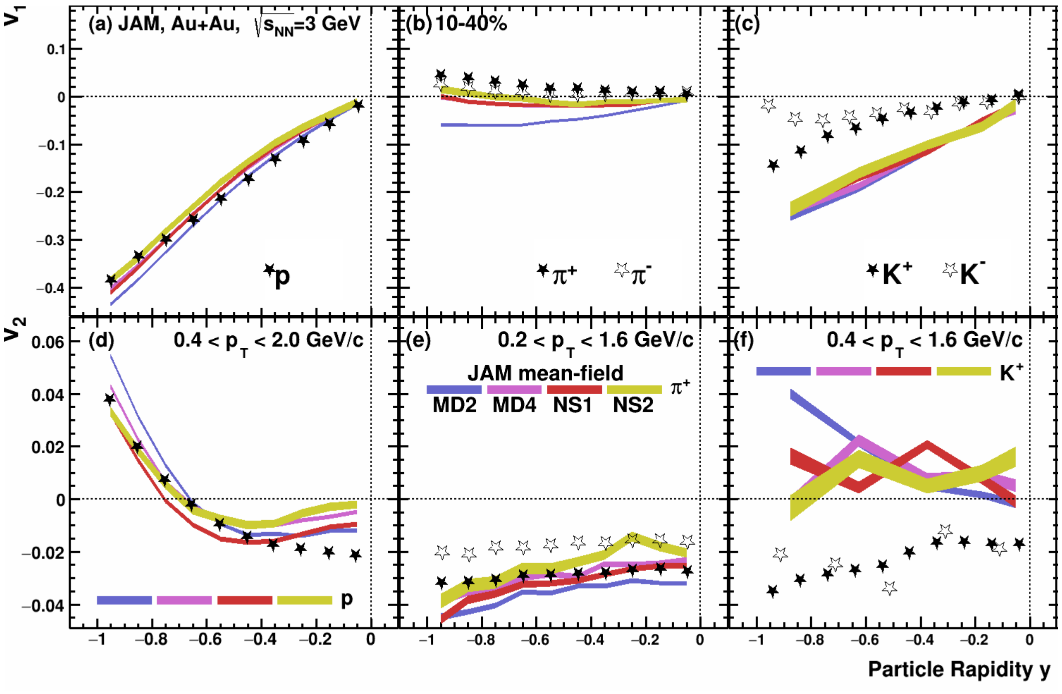
Elliptic flow:



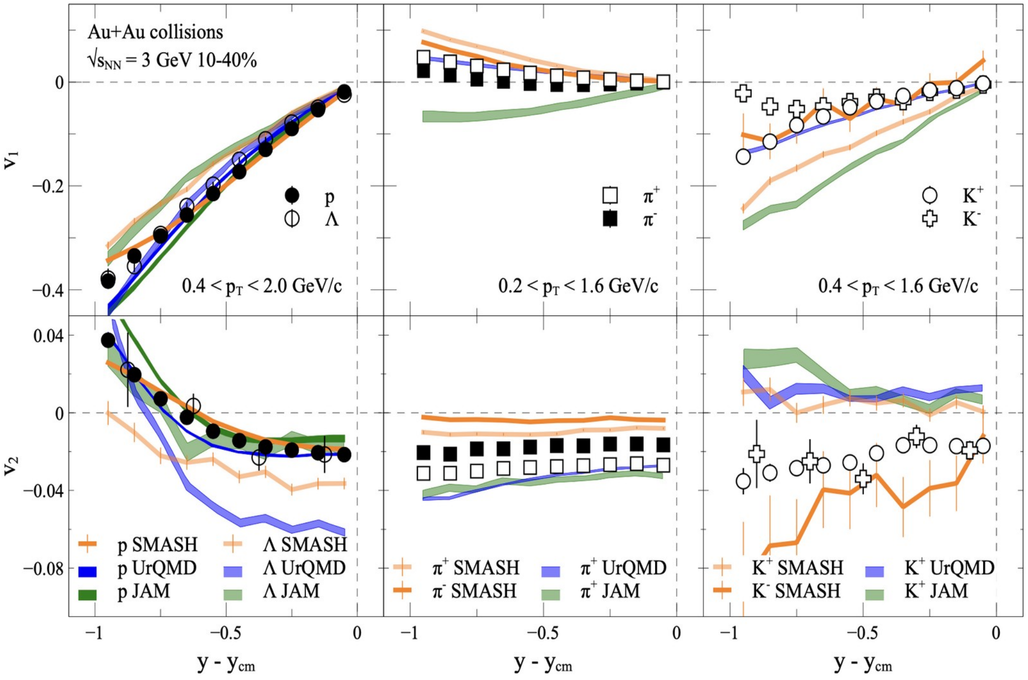


$dN/d\Phi \propto (1 + 2v_1 \cos\Phi + 2v_2 \cos 2\Phi)$

in Au+Au =3 GeV: model vs. STAR data



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

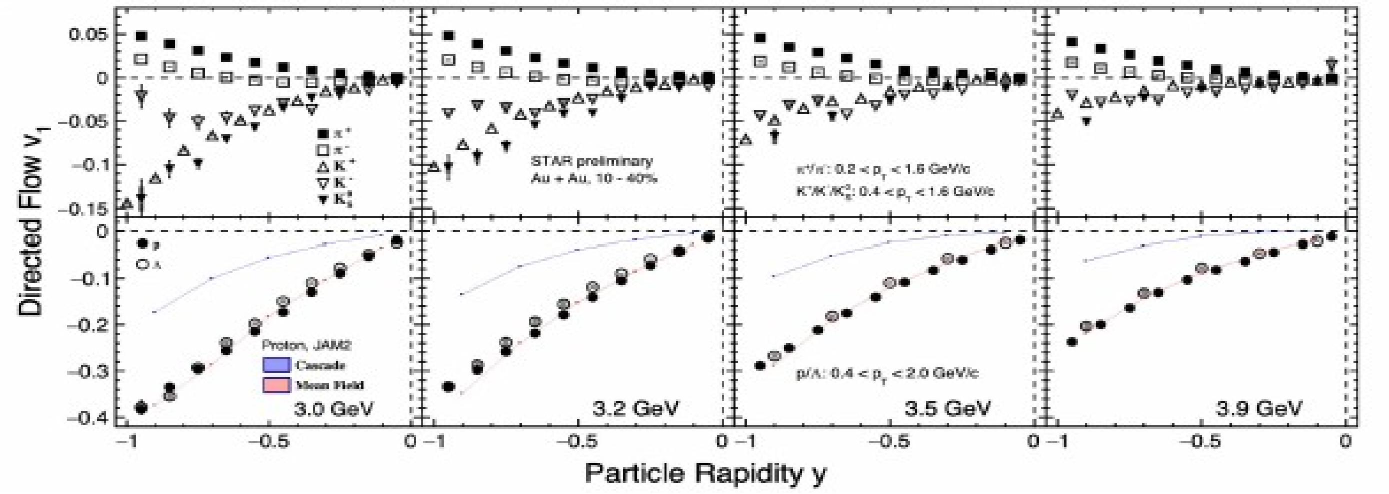


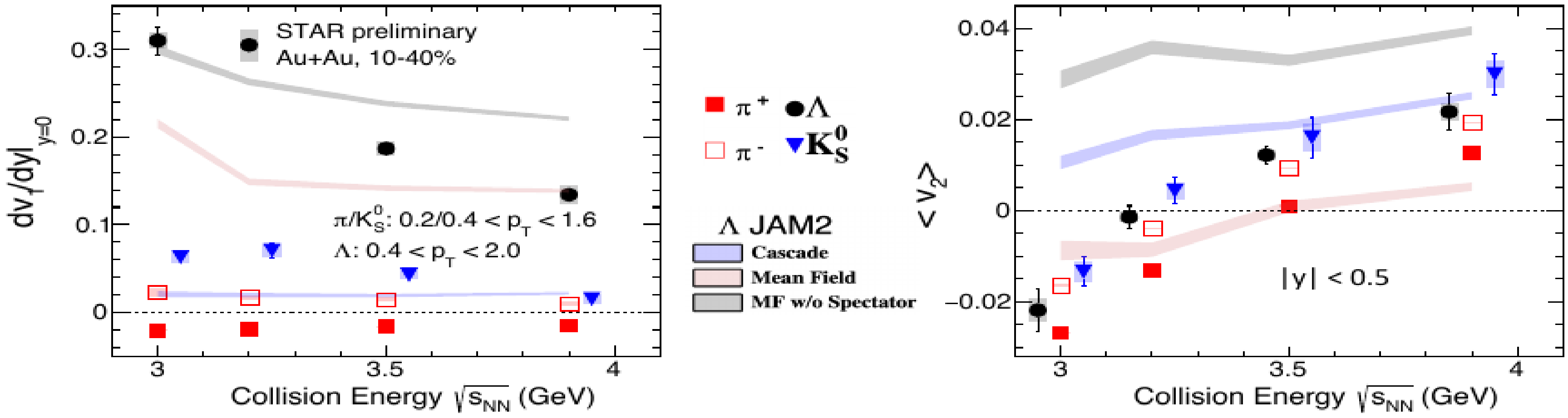
A. Sorensen et. al., arXiv:2301.13253 [nucl-th] (2023)

Models do not describe all particle species equally well

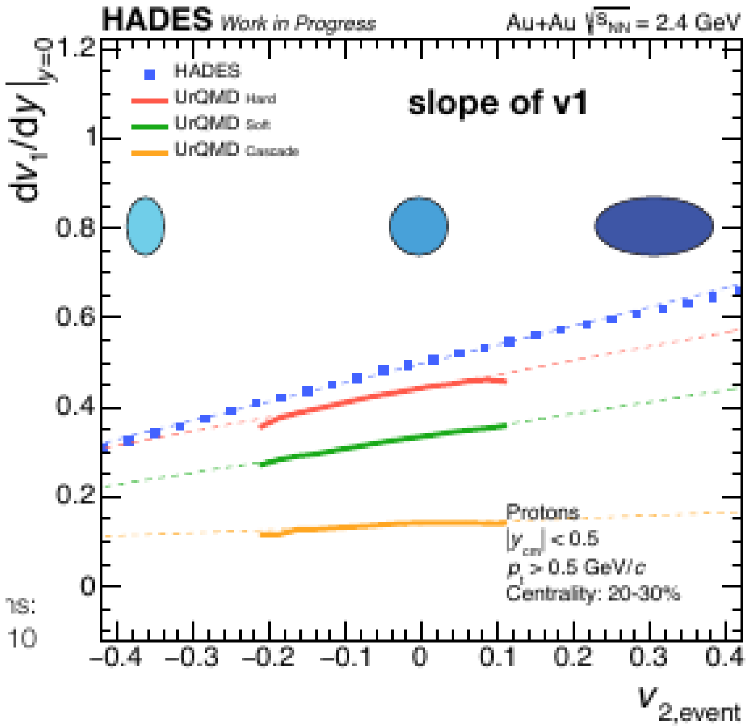
, of protons are described by JAM, UrQMD (hard EOS) and SMASH (hard EOS with softening at higher densities)

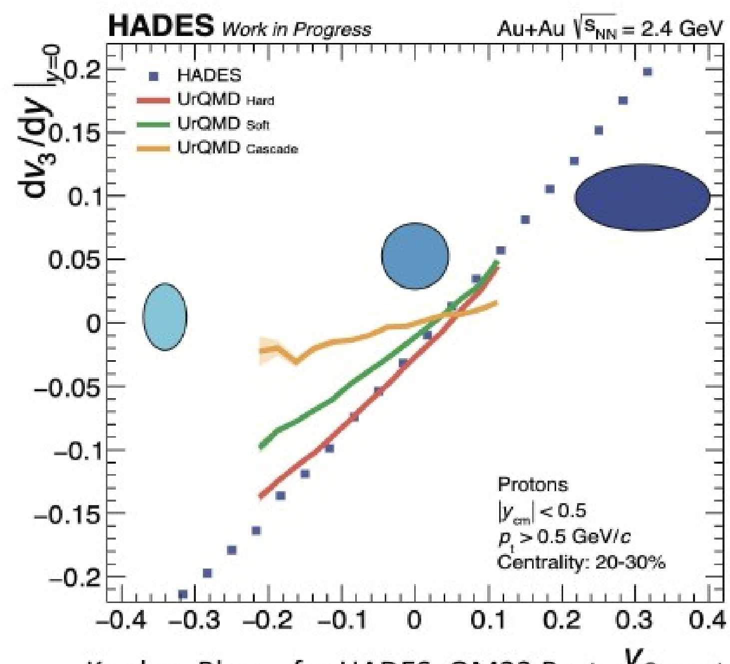
New STAR results from BES – II program were presented at QM2023





New HADES results





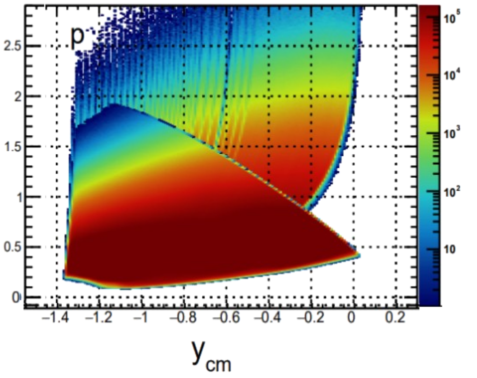
Kardan, Blume for HADES. QM23 Poster

RHIC BES programs

- Data taking by STAR at RHIC: 3 < < 200 GeV (750 < ⌞ $_B$ < 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),

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 viscosity, etc.
- **v_n at NICA energies shows strong energy dependence:**
  - At $\sqrt{s_{NN}}$=4.5 GeV v_2 from UrQMD, SMASH are in a good agreement with the experimental data
  - At $\sqrt{s_{NN}}$≥7.7 GeV UrQMD, SMASH underestimate v_2 – need hybrid models with QGP phase
  - Detailed JAM model calculations for differential measurements of v_n at $\sqrt{s_{NN}}$ = 2.4-4.5 GeV

  - The multi-differential high-statistics data from STAR/HADES/BM@N/MPD should enable a direct extraction of the EOS parameters at high baryon density via a Bayesian fit of the models to the data.

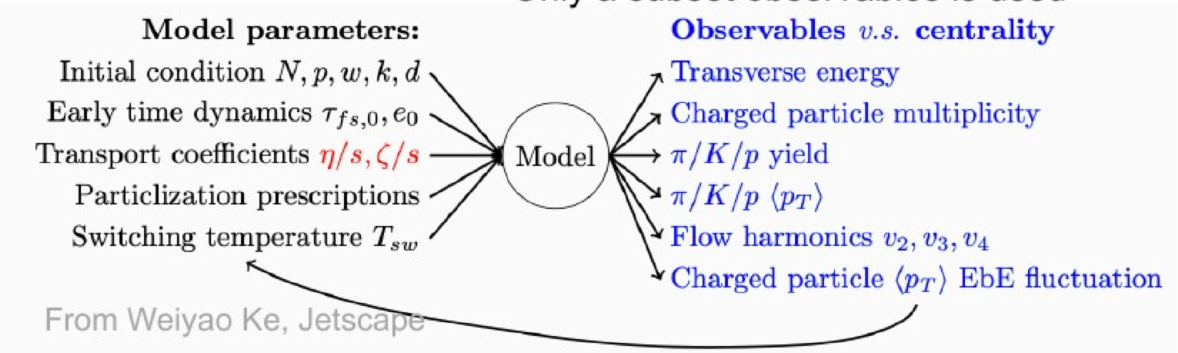
BM@N/NICA energies are very interesting: transition between hadronic and partonic matter?

Back-up slides

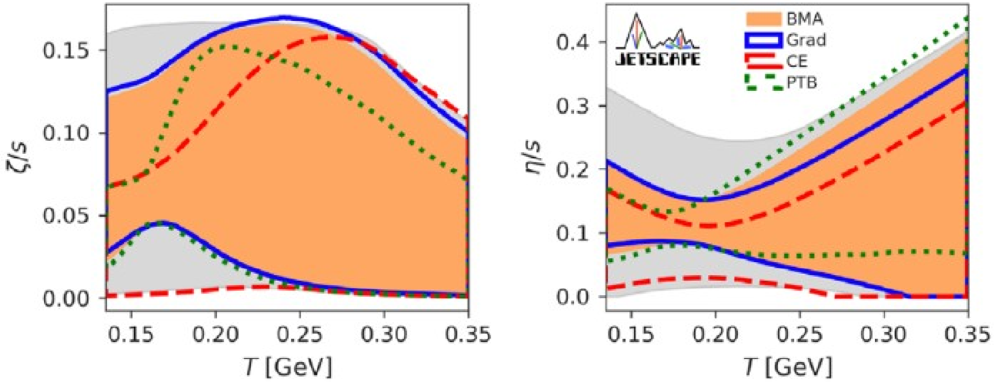
State-of-the-art modeling of HI collisions

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

Only a subset observables is used



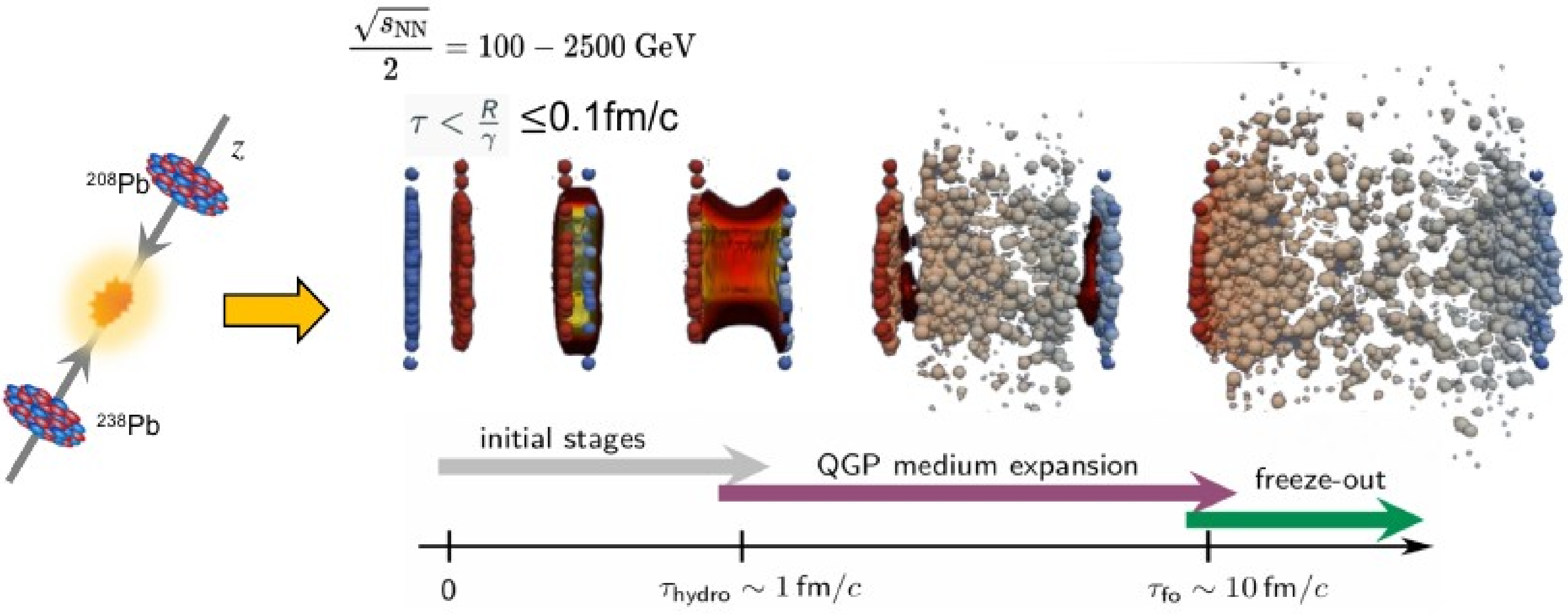
- Detailed temperature dependence of viscosity!



Jetscape PRL.126.242301
Trjactum PRL.126.202301

Major uncertainty: initial condition and pre-hydro phase

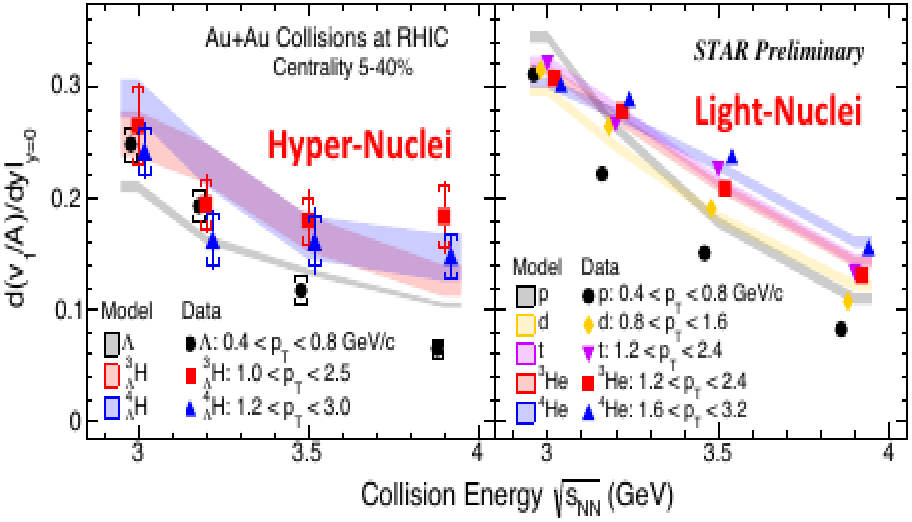
High-energy heavy ion collision



400 nucleons → 30000 hadrons

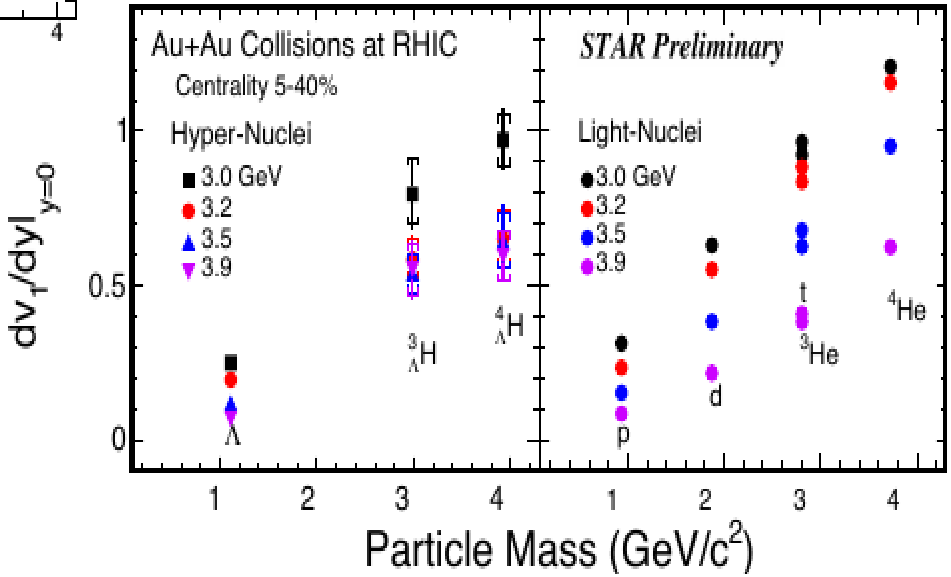
in 10^{-23} seconds

1) Extremely short passing time to take a snap-shot of the nuclear wavefunction in the two nuclei.
2) Large particle production in overlap region means QGP is dense and expand hydrodynamically.



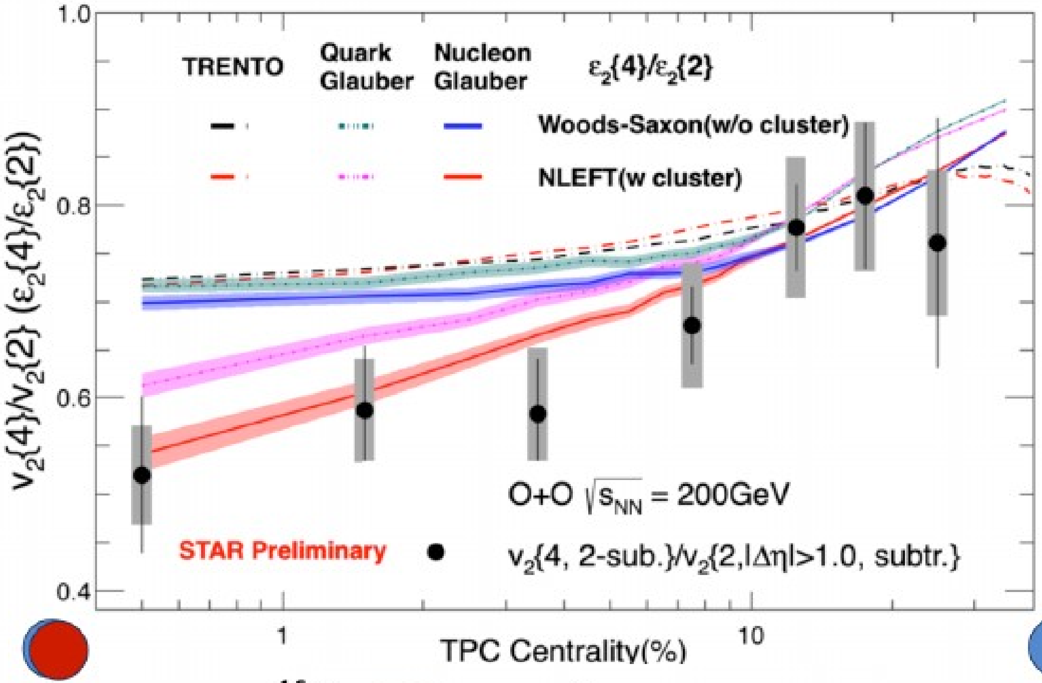
- Hypernuclei at high μ_B can probe Y-N (hyperon-nucleon) interactions
  - Useful for neutron stars!
- v_1: Consistent w/Hadronic transport model
  - Decreases with increasing collision energy

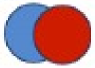
1.B. E. Aboona *et al.*, (STAR Collaboration), Phys. Rev. Lett. **130**, 211301(2023)

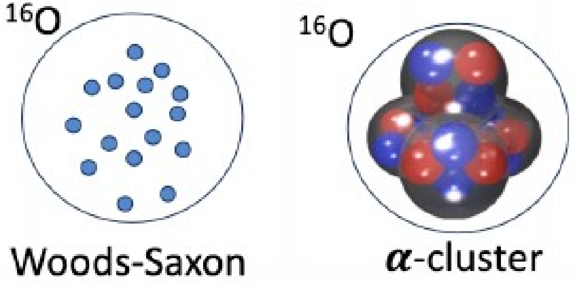


- The slopes of mid-rapidity v_1 for both light- and hyper-nuclei are scaled with A and/or mass
  - Across multiple collision energies
  - Coalescence

Substructure of Oxygen







$v_2\{2\}$ - sensitive to fluctuations

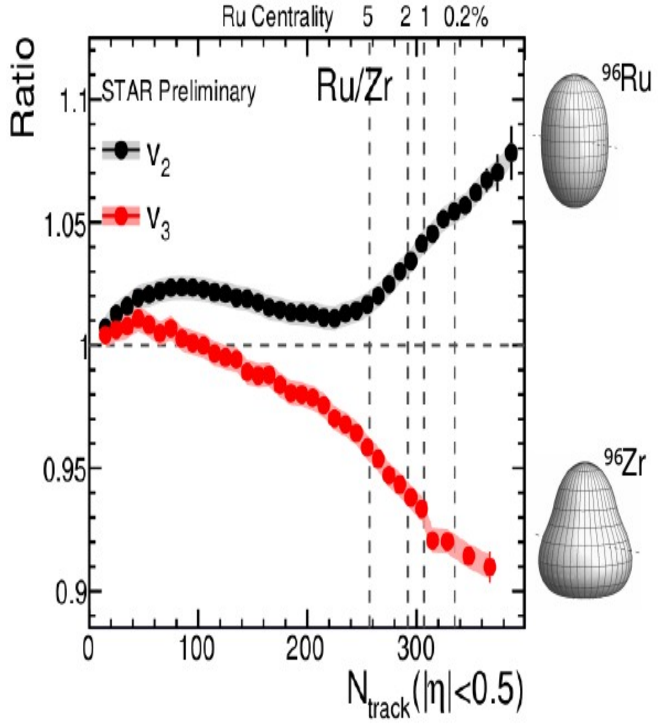
$v_2\{4\}$ - reduced sensitivity to fluctuations

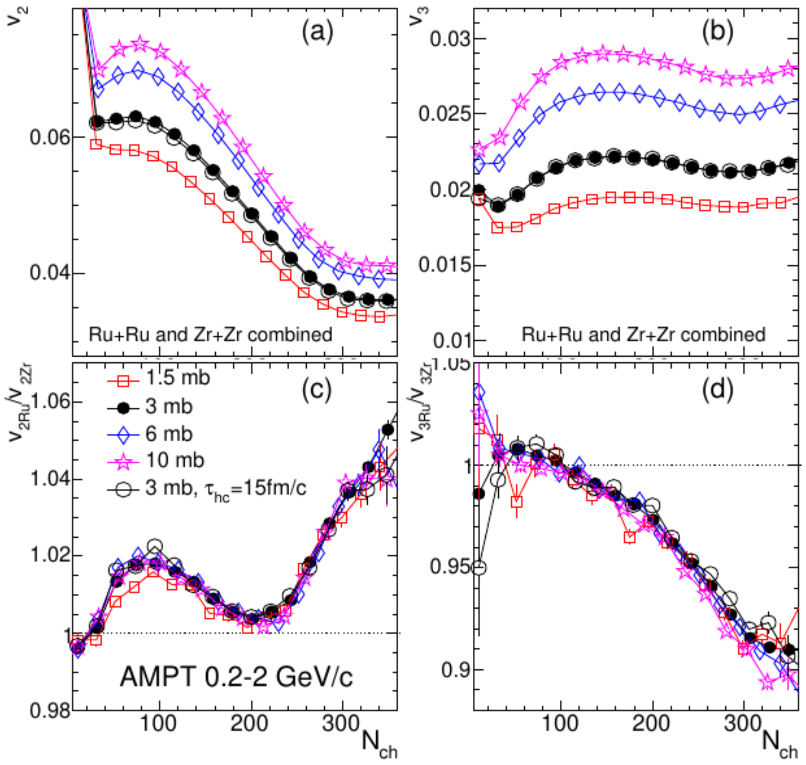
Data:
in central event but fluctuations enhanced, (v_2 reduced overall)

Theory:
Alpha clusters enhance fluctuations

Data strongly favor alpha-clustering

2022: Nuclear structure via V_n ratio





Phys.Rev.C 105 (2022) 1, 014901 • e-Print: 2109.00131

The V_n ratio for isobars – not affected by final state – is a good tool for precision studies of nuclear shapes.

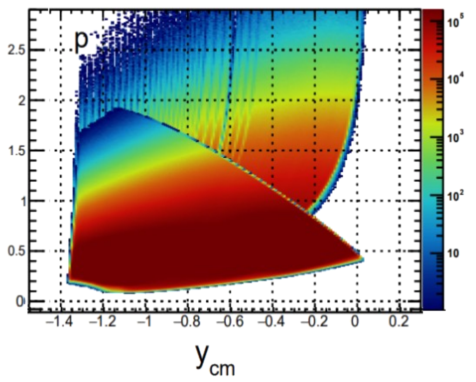
RHIC BES programs

- Data taking by STAR at RHIC: 3 < < 200 GeV (750 < ⌙ $_B$ < 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

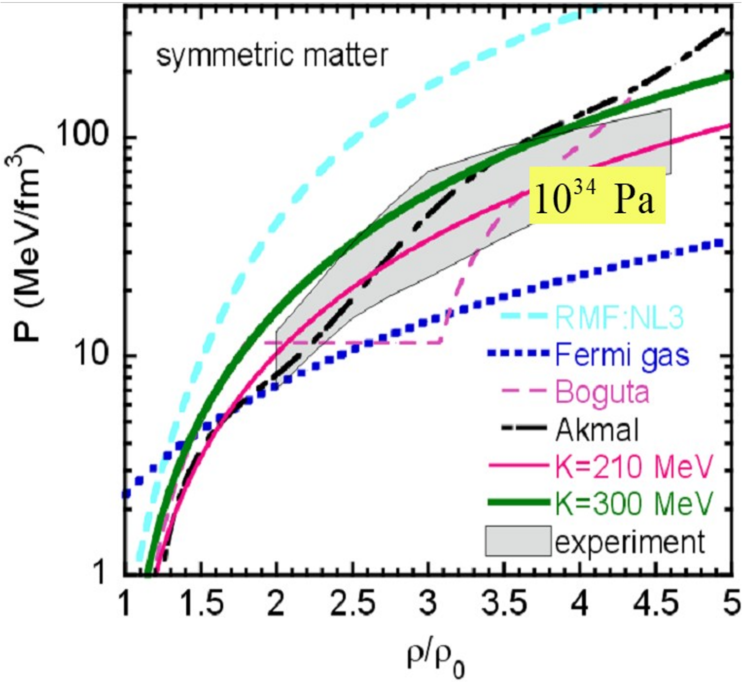
Au+Au @ 3.9 GeV



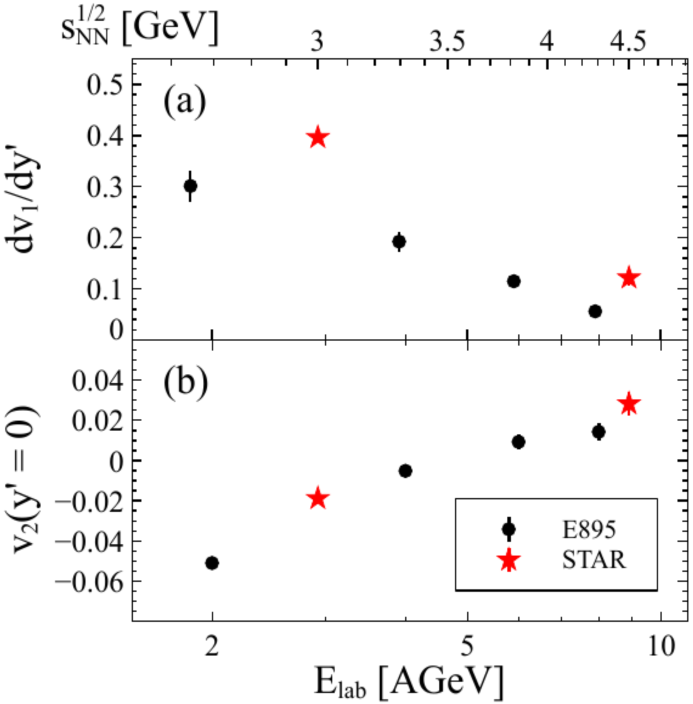
- A very impressive and successful program with many collected datasets, already available and expected results
- Limitations:
  - ✓ Au+Au collisions only
  - ✓ Among the fixed-target runs, only the 3 GeV data have full mid-rapidity coverage for protons (|y| < 0.5),

Flow at AGS: Constraints for the Hadronic EOS

Danielewicz, Lacey, Lynch,
Science 298 (2002) 1592-1596

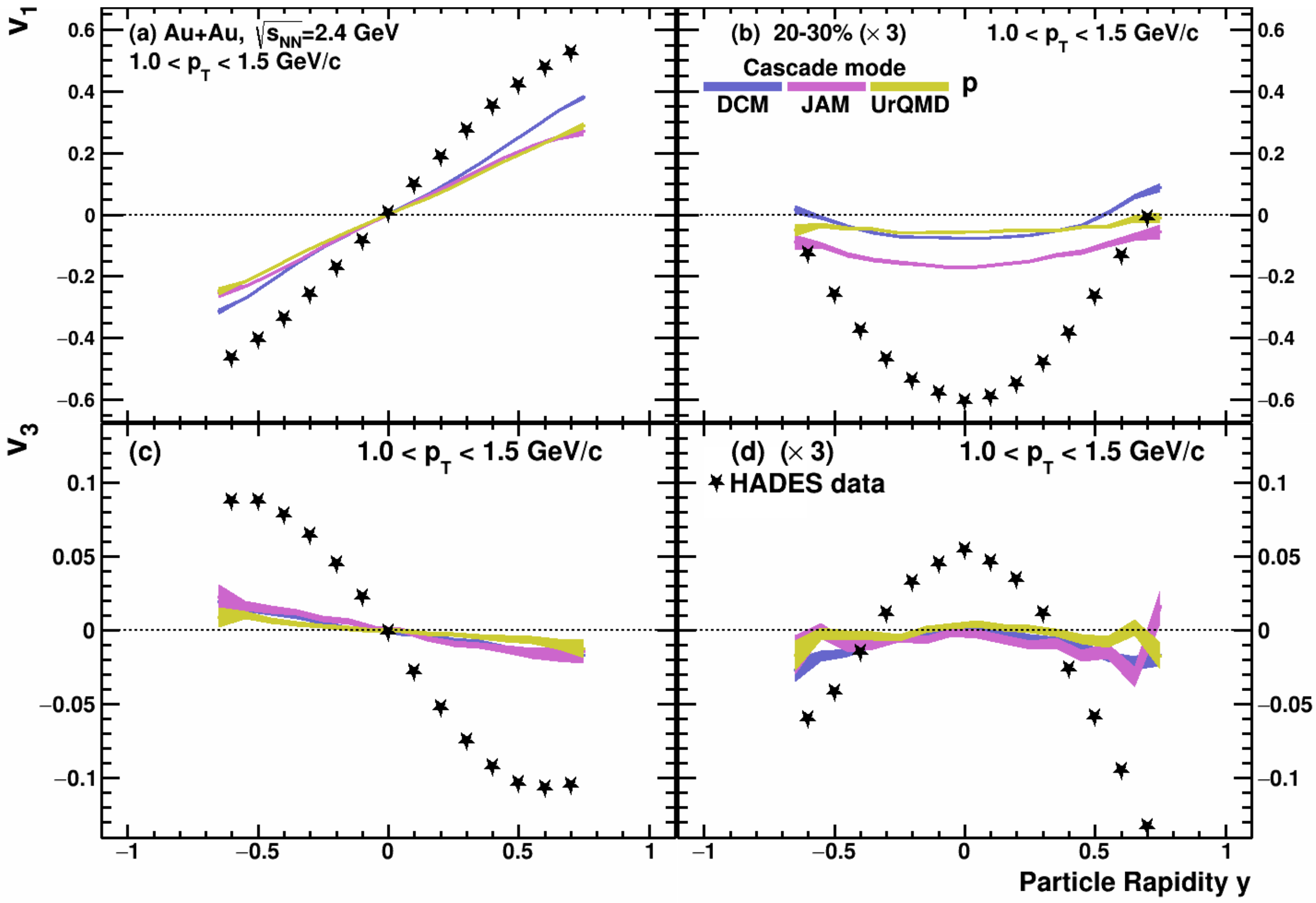


https://arxiv.org/abs/2208.11996



The main source of existing systematic errors in measurements is the difference between results from different experiments. New STAR measurements from BES II will provide better **constraints for the Hadronic EOS**

in Au+Au =2.4 GeV: cascade models

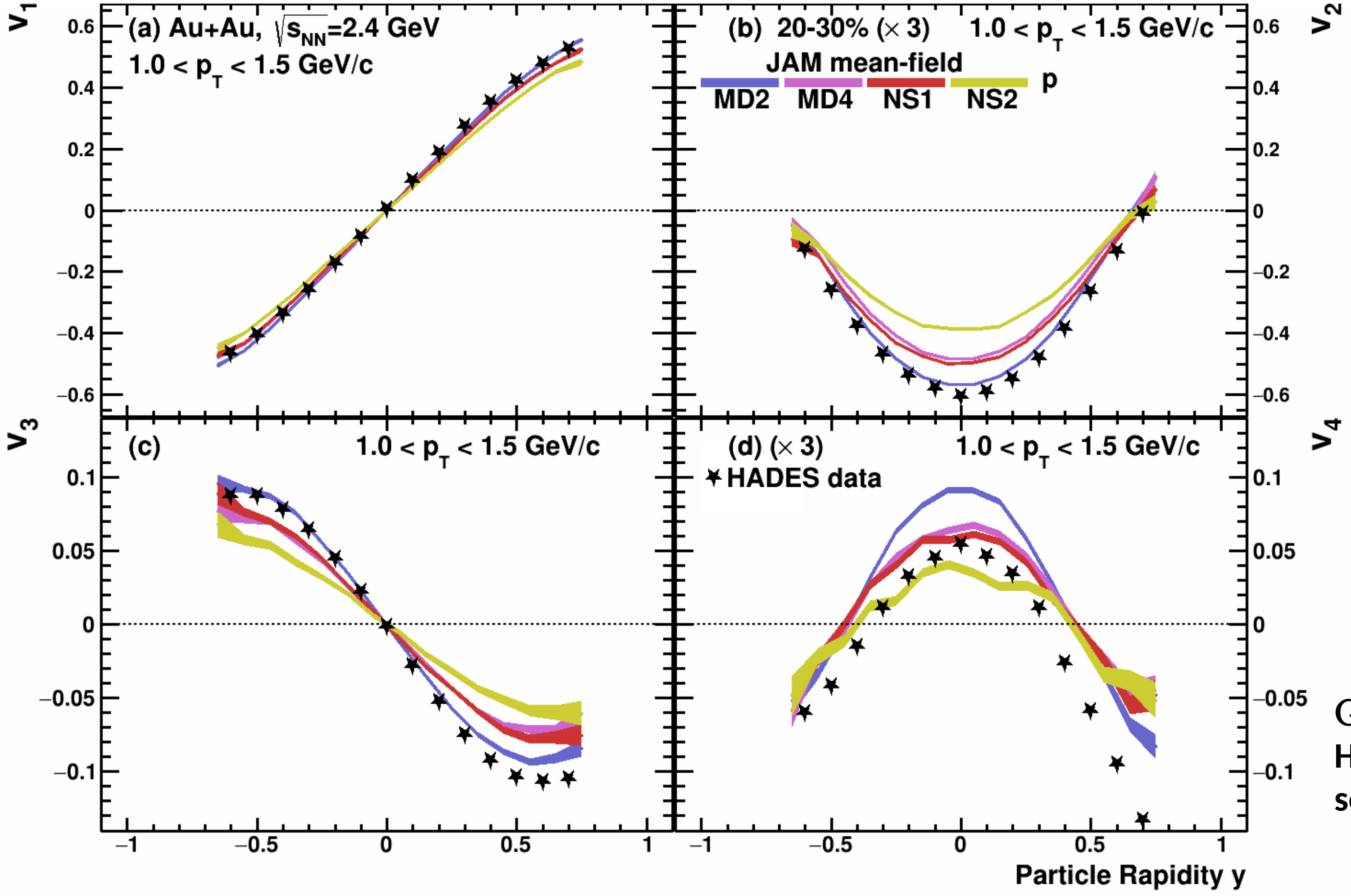


P. Parfenov, Particles 5, no.4, 561-579 (2022

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

in Au+Au =2.4 GeV: model vs. HADES data



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

Kinematic cuts:

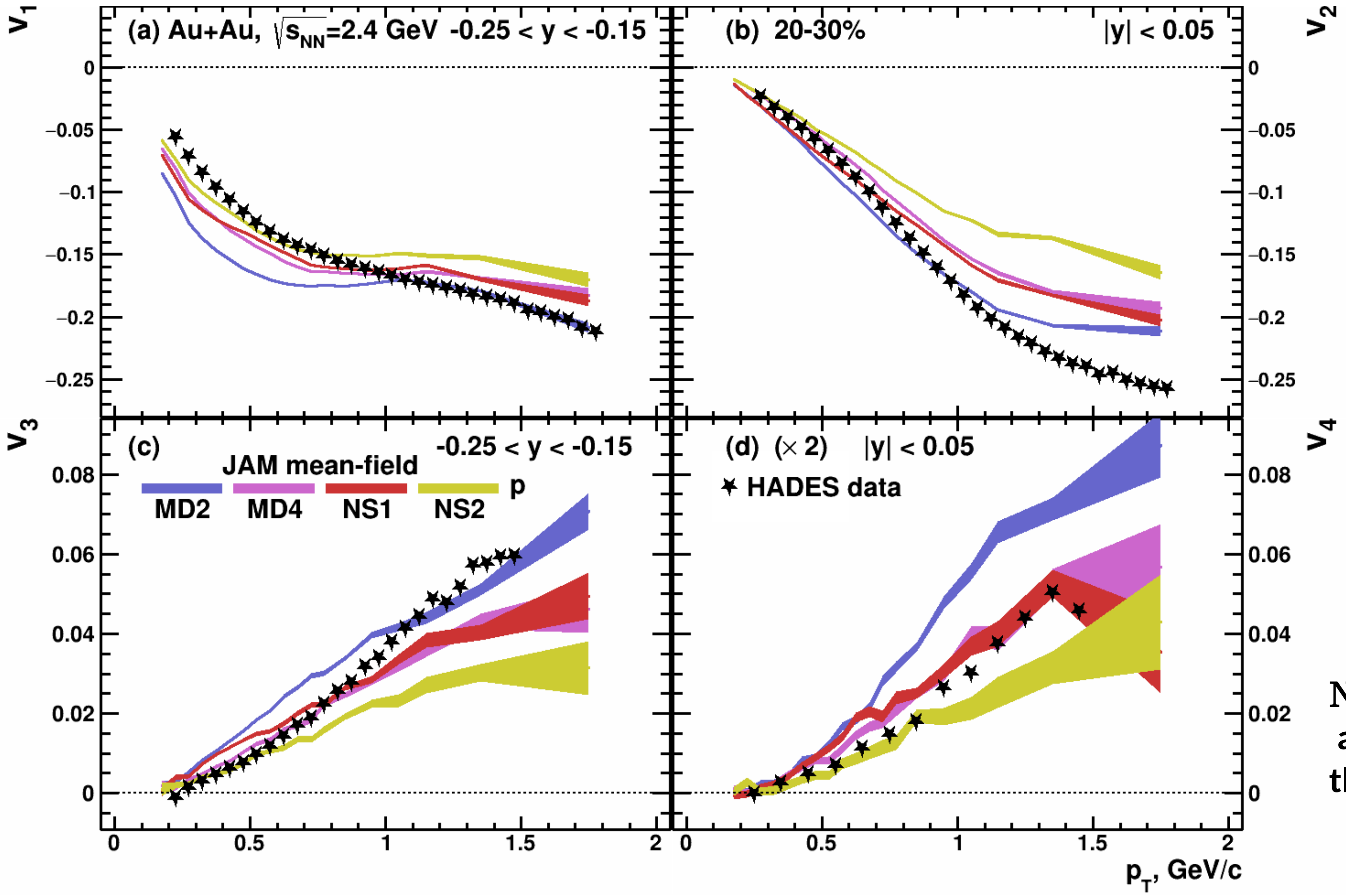
$V_{1,3}(y)$: 1.0 < pT < 1.5 GeV/c

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

Good agreement for

Higher harmonics are more sensitive to different EOS than

in Au+Au =2.4 GeV: model vs. HADES data

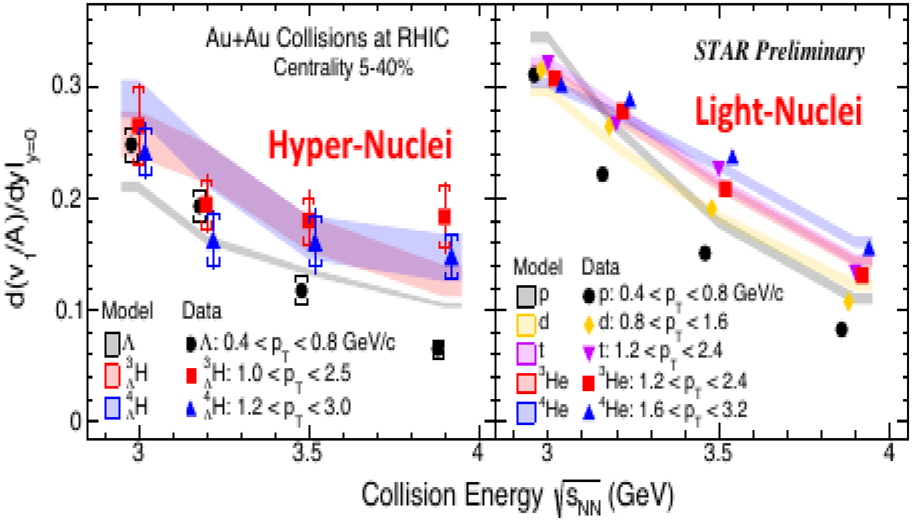


Experimental data points:
Phys. Rev. Lett. **125** (2020) 262301

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

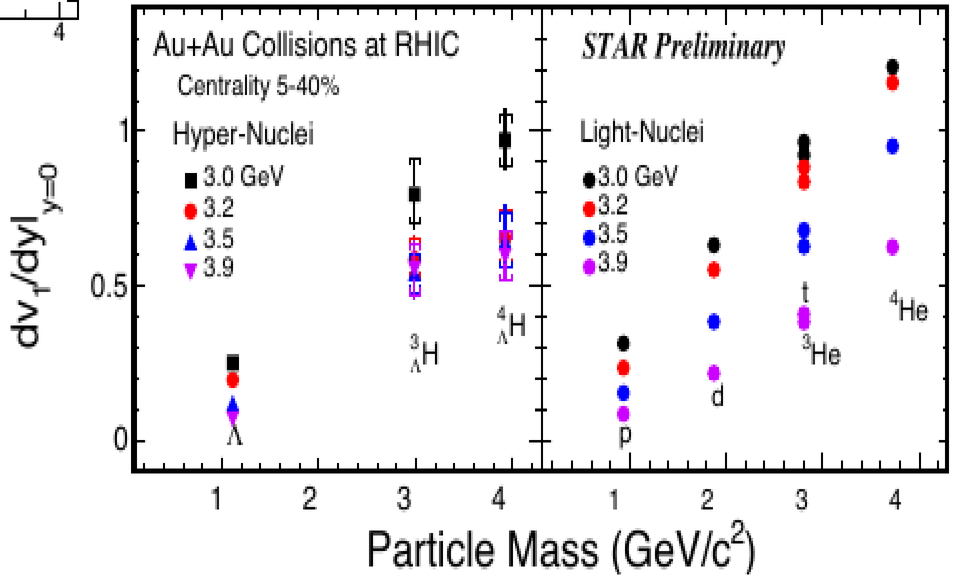
Not a good agreement for
are more sensitive to different EOS than

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



- Hypernuclei at high μ_B can probe Y-N (hyperon-nucleon) interactions
  - Useful for neutron stars!
- v_1: Consistent w/Hadronic transport model
  - Decreases with increasing collision energy

1.B. E. Aboona *et al*., (STAR Collaboration), Phys. Rev. Lett. **130**, 211301(2023)



- The slopes of mid-rapidity v_1 for both light- and hyper-nuclei are scaled with A and/or mass
  - Across multiple collision energies
  - Coalescence