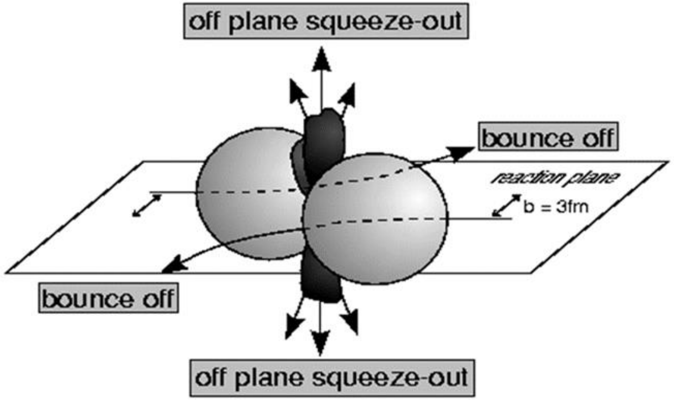
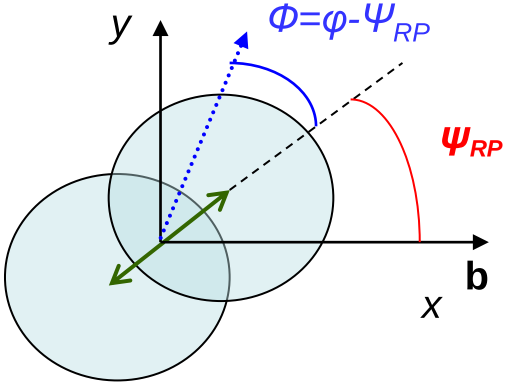
Измерения анизотропных коллективных потоков от LHC до NICA

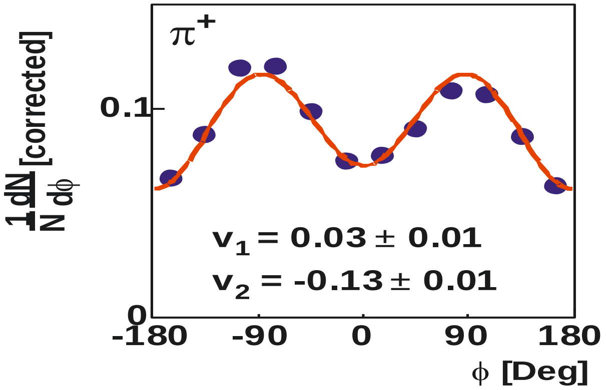
Аркадий Тараненко (НИЯУ МИФИ, ЛФВЭ ОИЯИ)

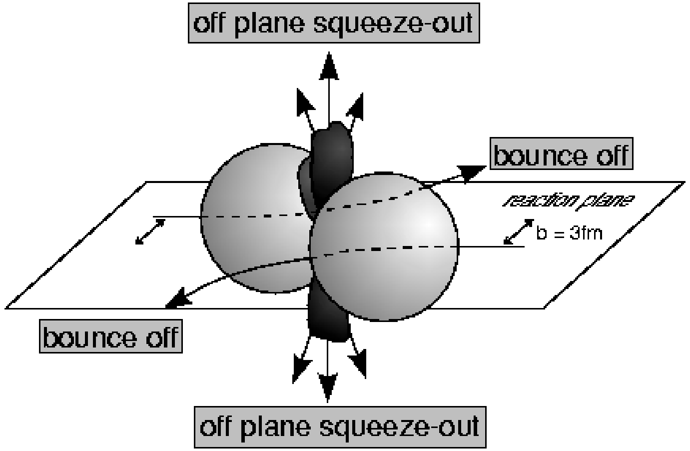


Научная сессия секции ядерной физики ОФН РАН, посвященная 300-летию Российской Академии Наук, ОИЯИ, 1-5 апреля 2024

Azimuthal anisotropy of particles at HIC 1989-2024







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

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

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

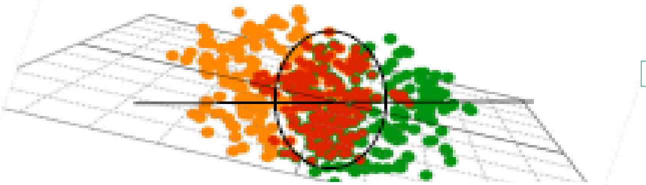
$$v_n=\langle\cos[n(\varphi-\Psi_{RP})]\rangle$$

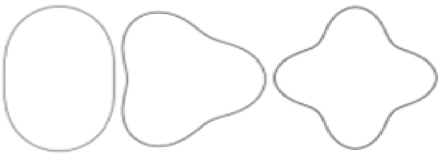
- ❑ Fourier coefficients $\mathbf{v_n}$ quantify anisotropic flow:

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



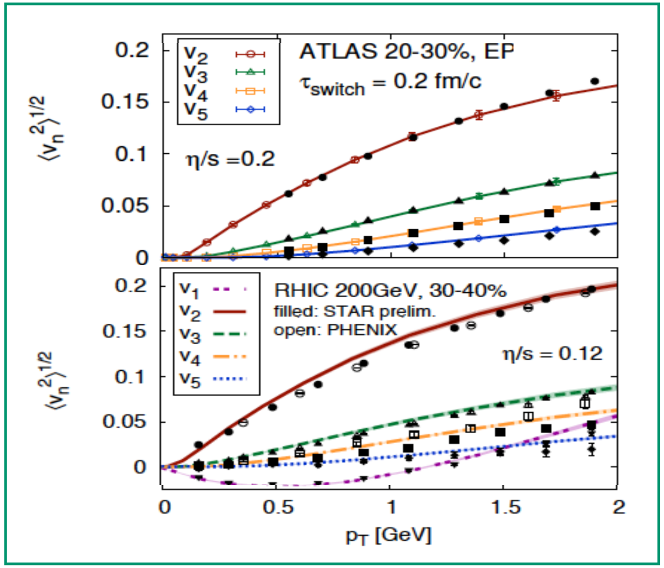


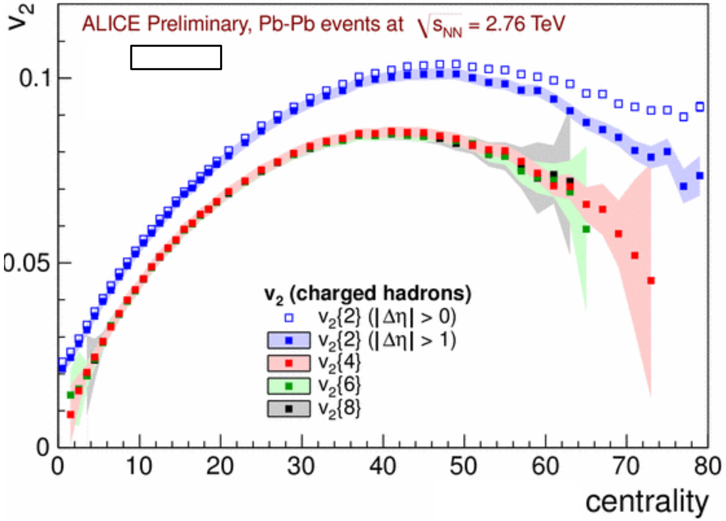
$$\epsilon_n = \sqrt{\frac{\langle r^n \cos n\phi\rangle + \langle r^n \sin n\phi\rangle}{\langle r^n\rangle}}$$

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

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



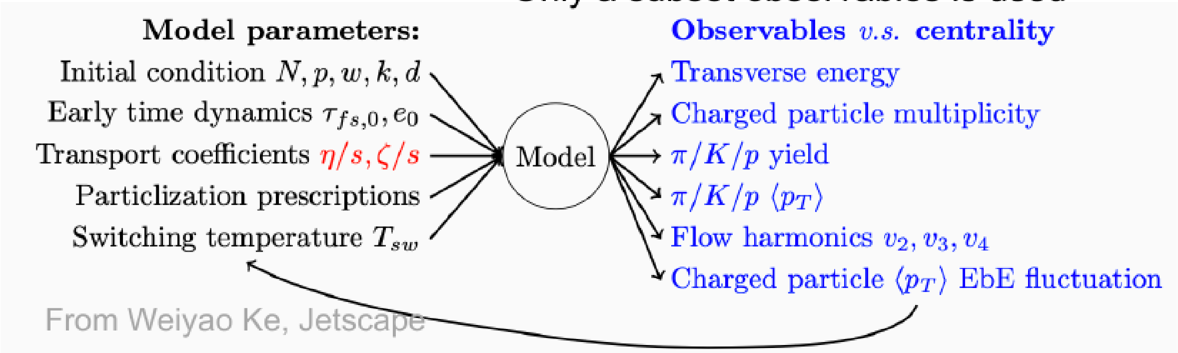


Flow and non-Flow, Fluctuations

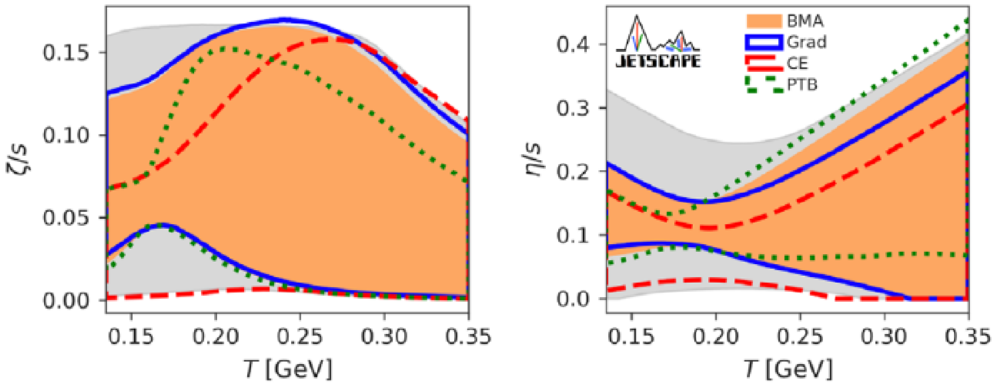
State-of-the-art modeling of HI collisions

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

Only a subset observables is used



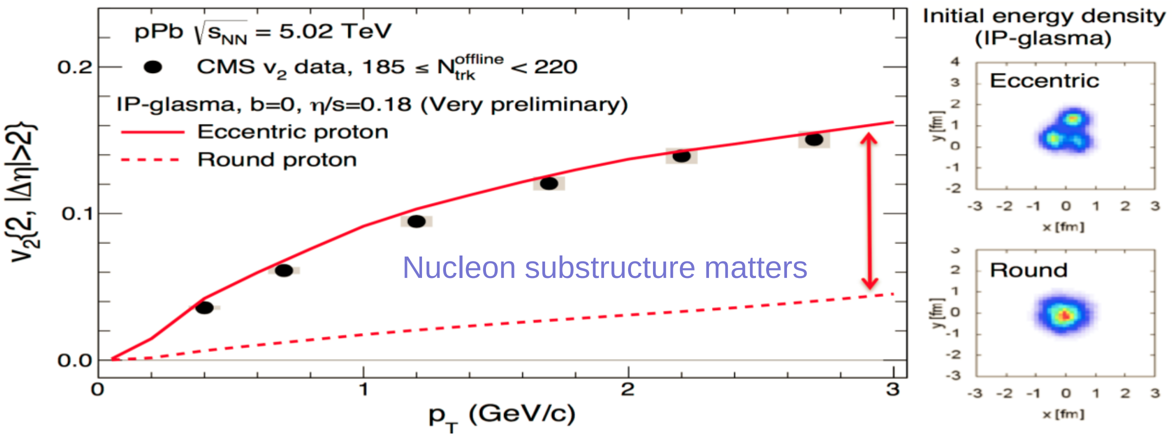
- Detailed temperature dependence of viscosity!



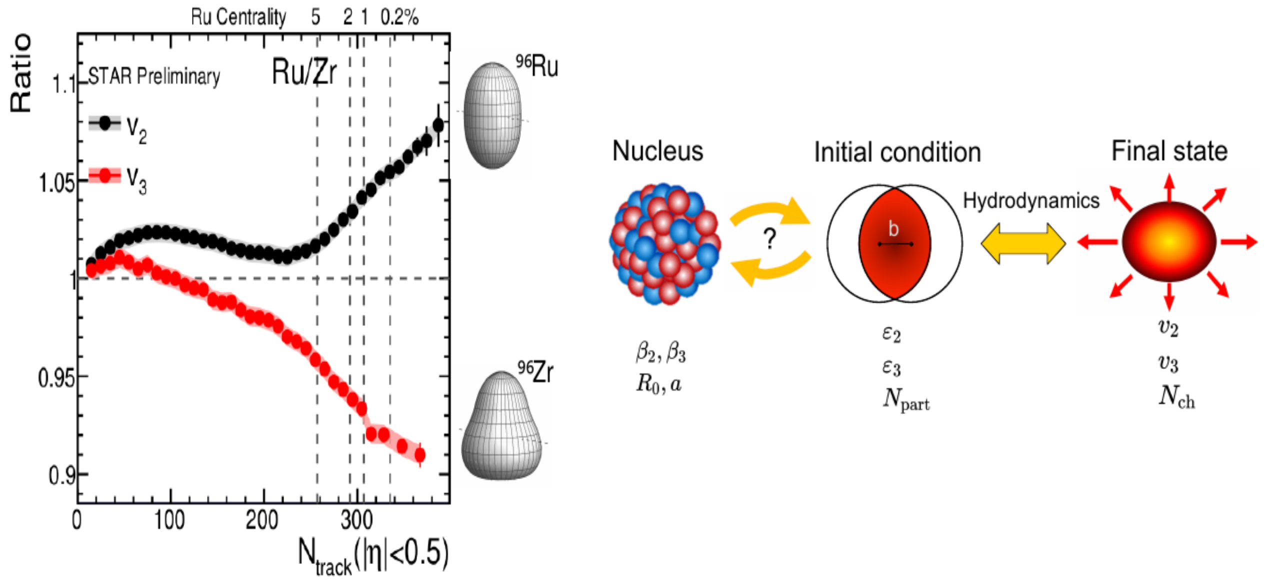
Jetscape PRL.126.242301
Trjactum PRL.126.202301

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

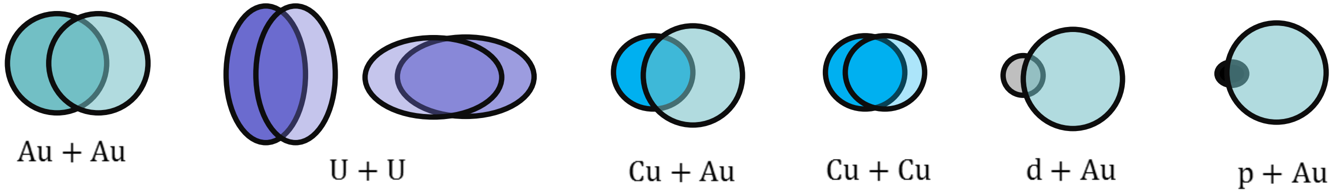
arXiv:1305.3341
Roy A. Lacey, et al.

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

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

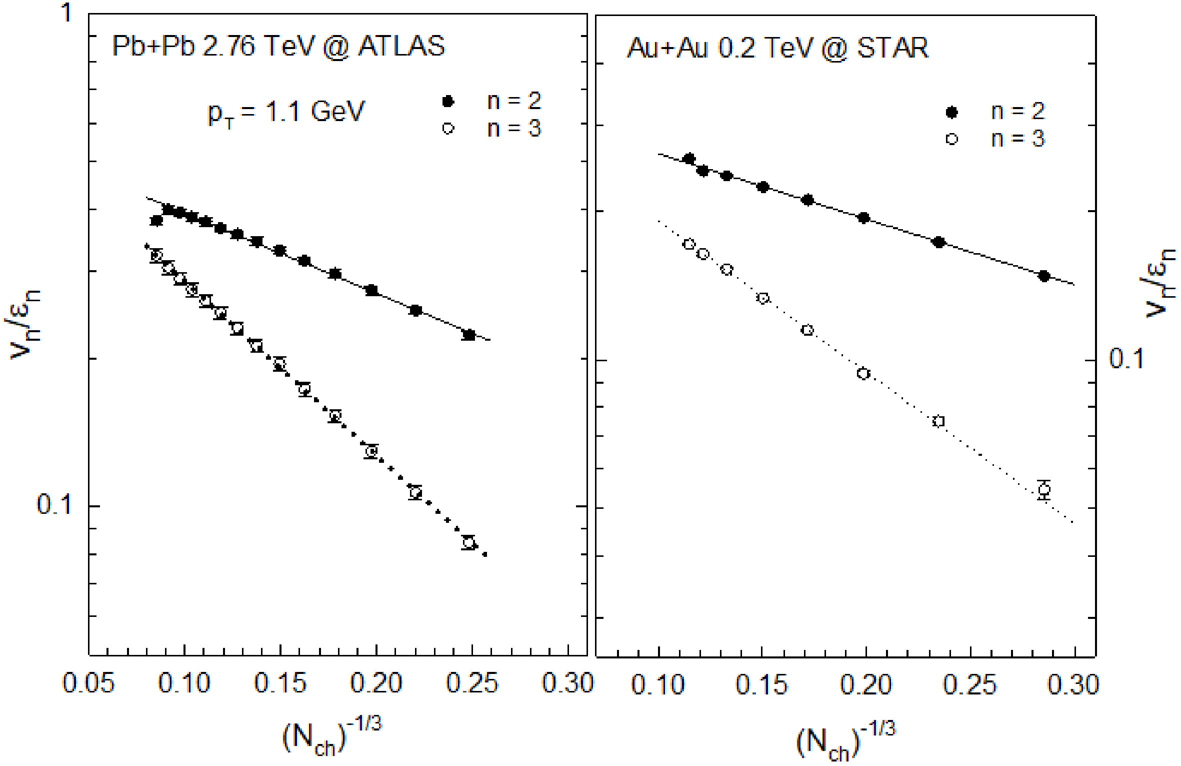


Scaling expected For *similar* $\frac{\eta}{s}$ *and* $\frac{dN}{d\eta}$

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**

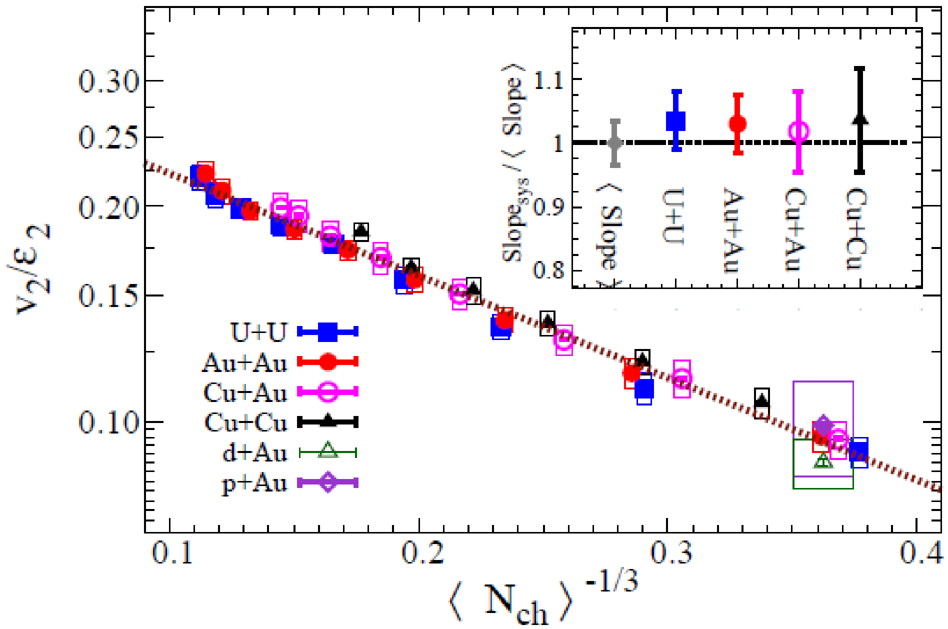
Flow is acoustic

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

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

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

- Anisotropic flow attenuation:

- From macroscopic entropy considerations:

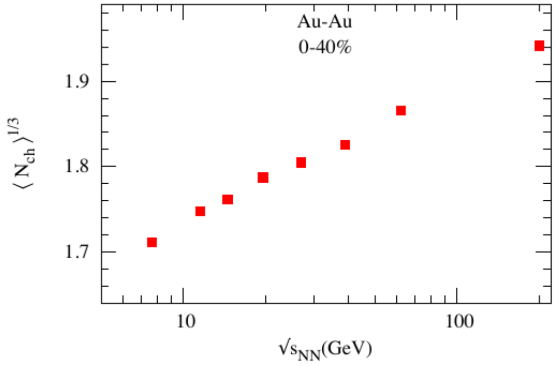
$$S \sim (RT)^3 \sim \langle N_{Ch} \rangle \text{ then } RT \sim \langle N_{Ch} \rangle^{1/3}$$

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

Using two different harmonics :

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

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



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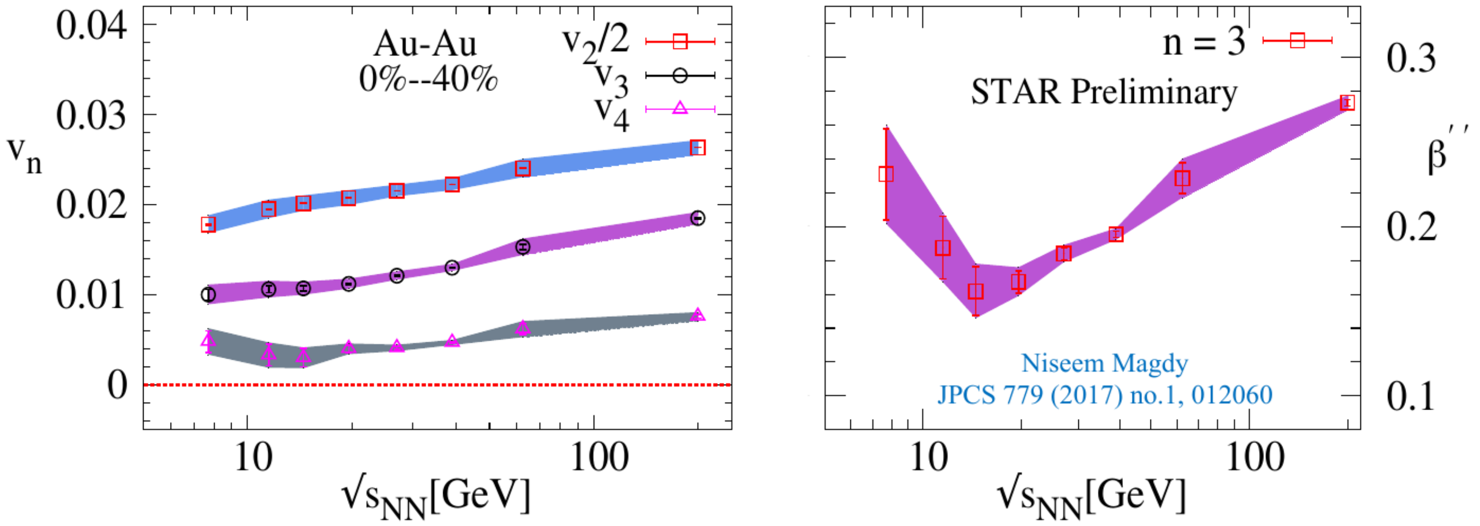
Beam energy dependence of V_n

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

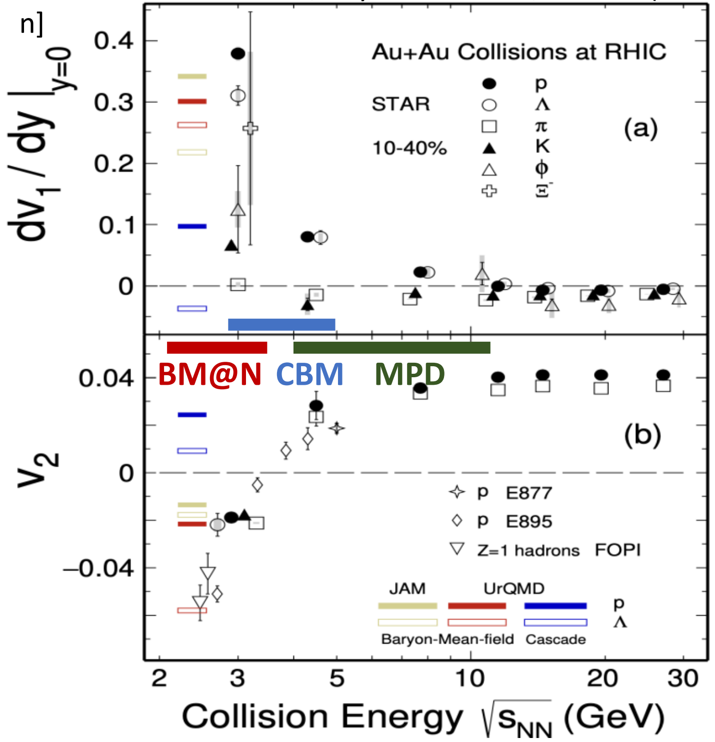
A: is constant

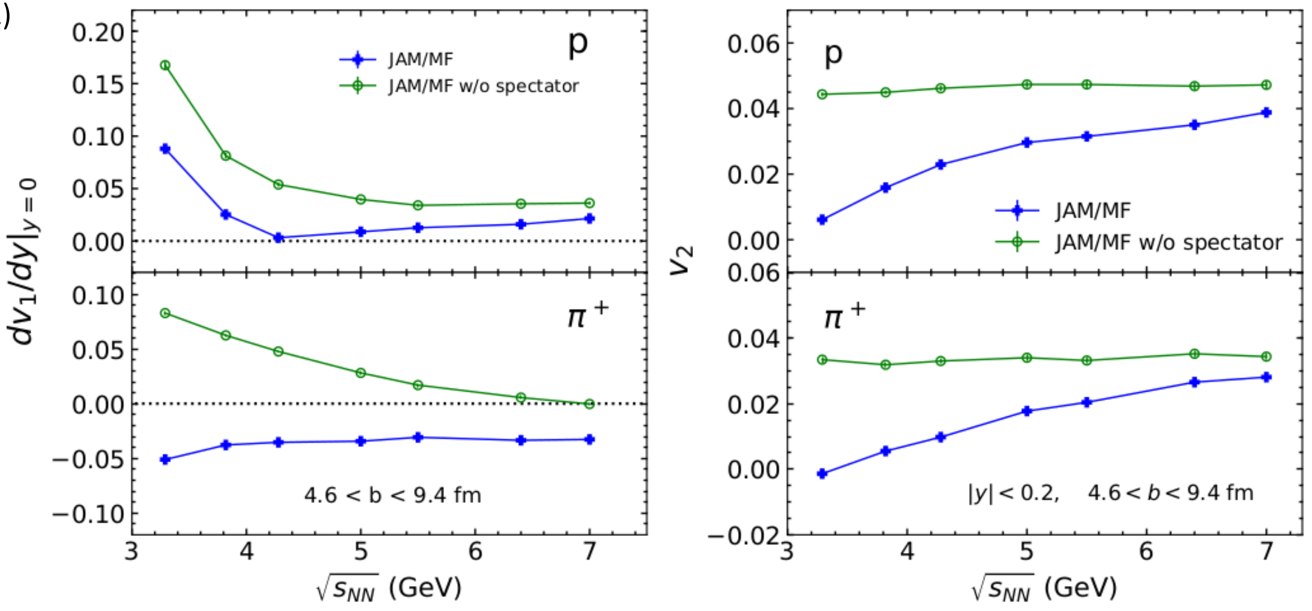


V_n shows a monotonic increase with beam energy. The viscous coefficient, which encodes the transport coefficient (***η*/*s***), indicates a non-monotonic behavior as a function of beam energy.

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

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





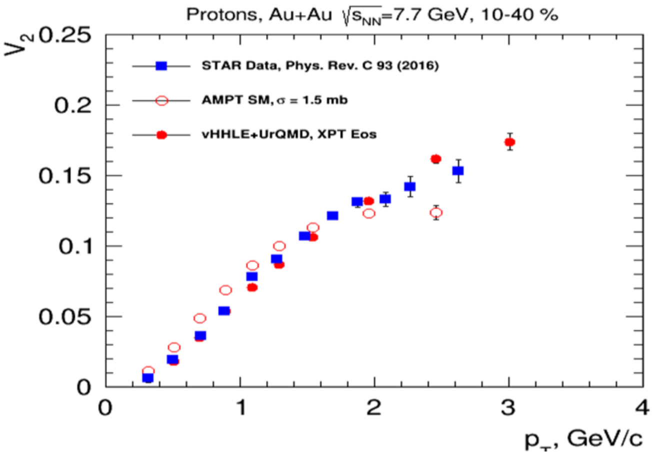
Phys. Rev. C 97, 064913 (2018)

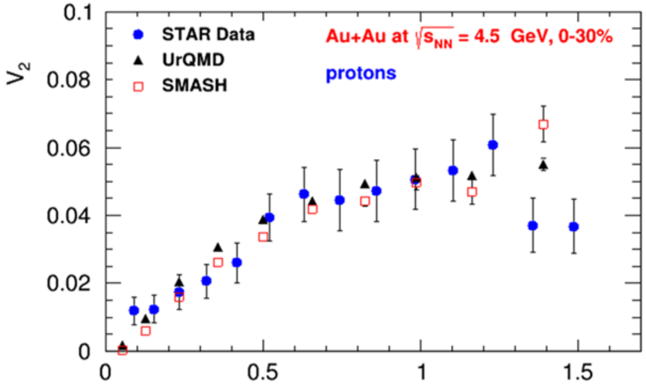
Anisotropic flow at FAIR/NICA energies is a delicate balance between:

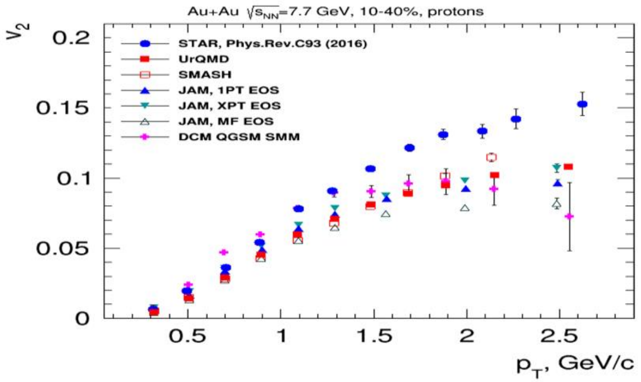
I. The ability of pressure developed early in the reaction zone ($t_{exp} = R/c_s \, , c_s = c\sqrt{dp/d\varepsilon}$) and

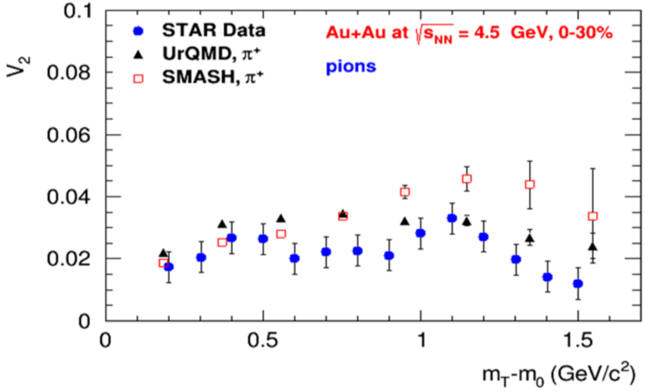
II. The passage time for removal of the shadowing by spectators ($t_{pass} = 2R/\gamma_{CM}\beta_{CM}$)

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



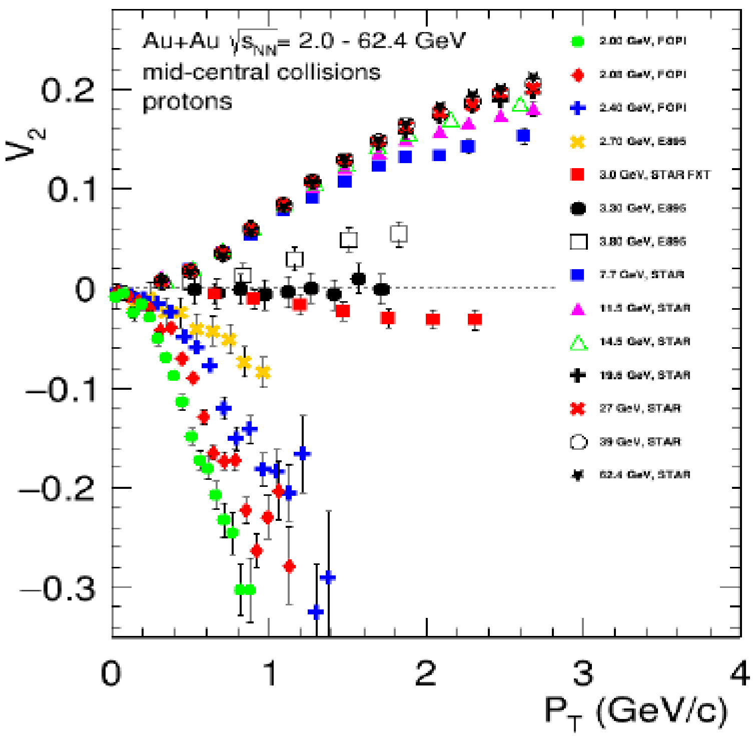


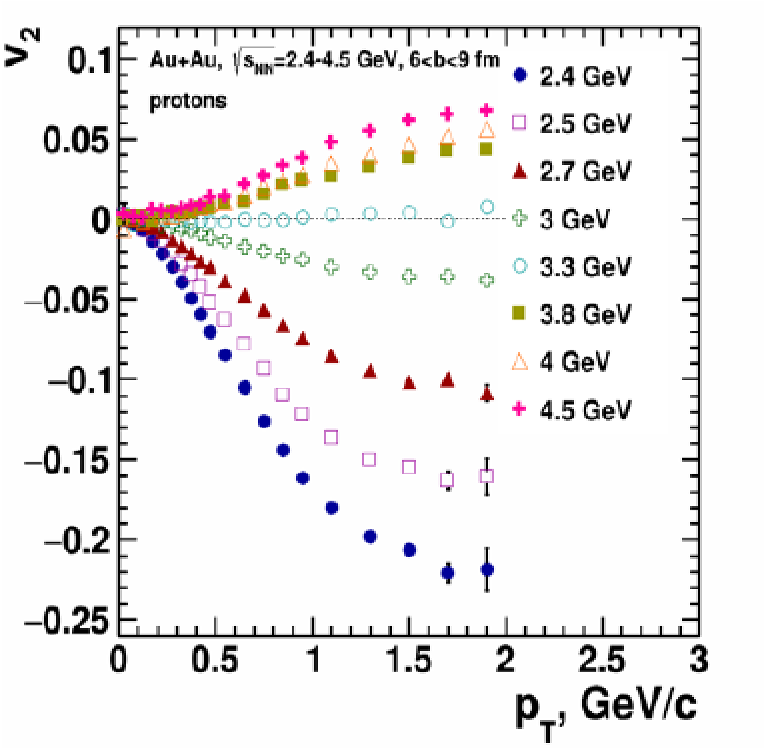




at $\sqrt{s_{NN}} \geq$ 7.7 GeV pure string/hadronic cascade models underestimate v_2 – need hybrid models with QGP phase (vHLLE+UrQMD, AMPT with string melting,...) at $\sqrt{s_{NN}} \geq$ 3-4.5 GeV pure hadronic models give similar v_2 signal compared to STAR data

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





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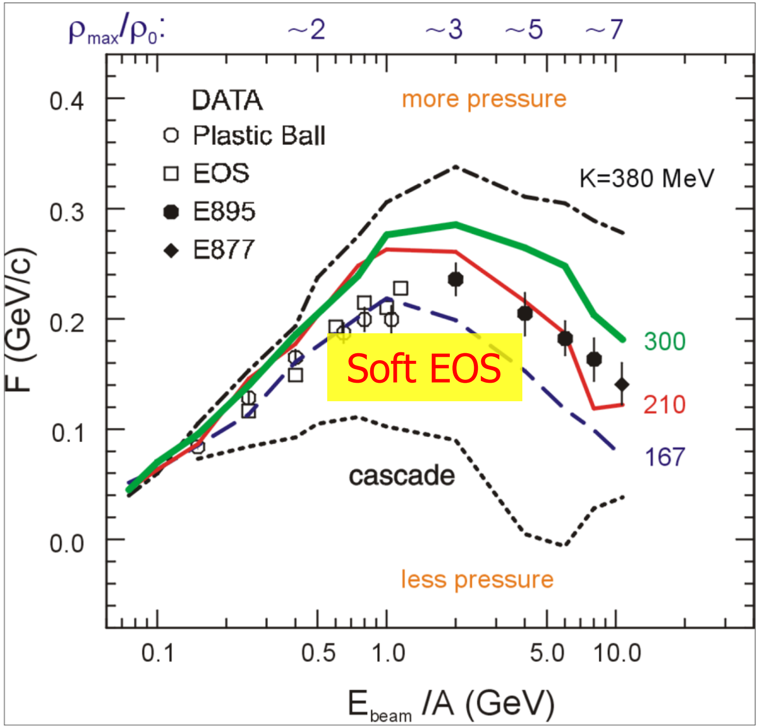
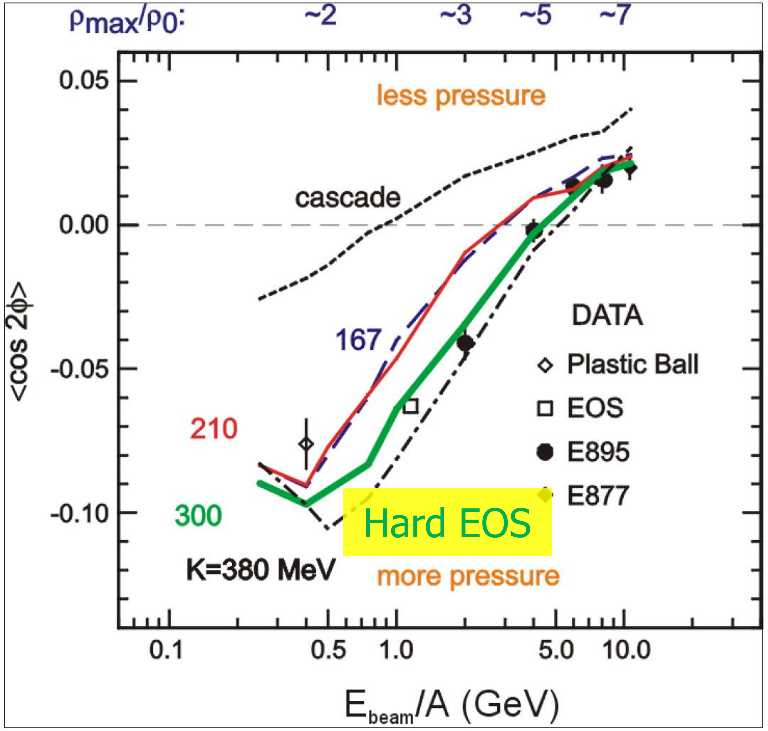
II. The passage time for removal of the shadowing by spectators ($t_{pass} = 2R/\gamma_{CM}\beta_{CM}$)

Nuclear incompressibility from collective proton flow

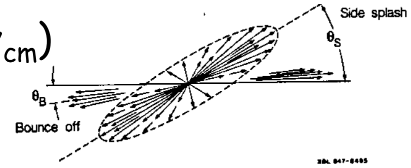
P. Danielewicz, R. Lacey, W.G. Lynch, Science 298 (2002) 1592



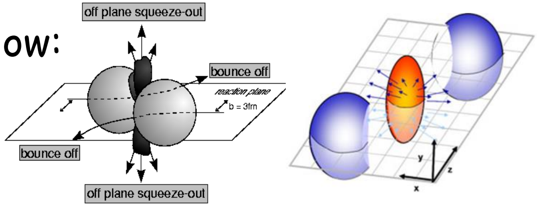


Transverse in-plane flow:

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

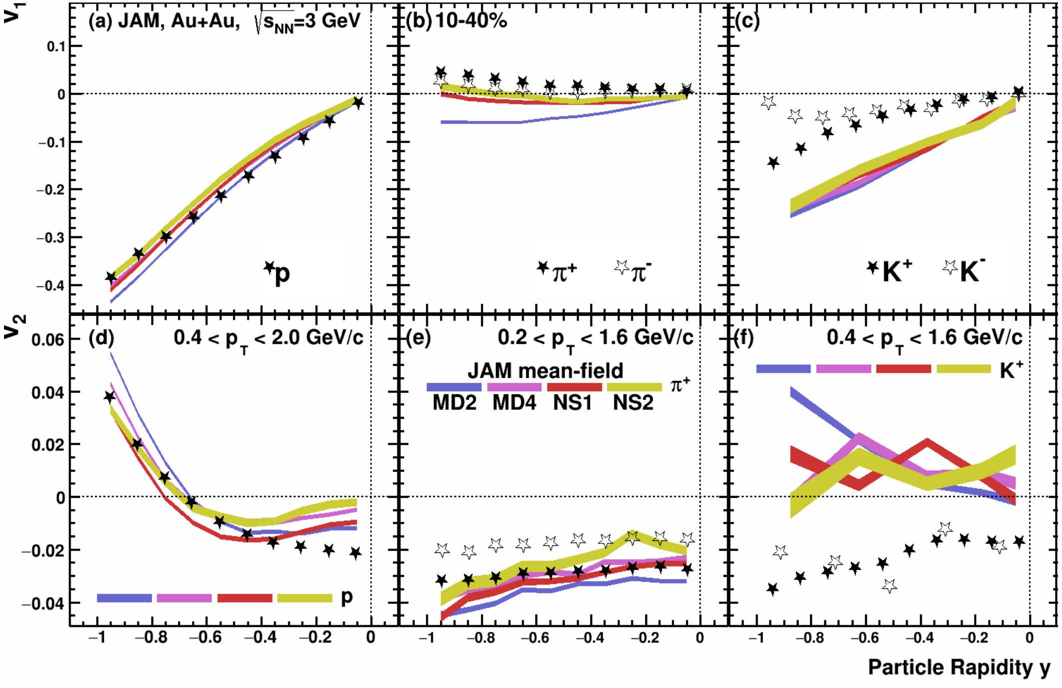


Elliptic flow:

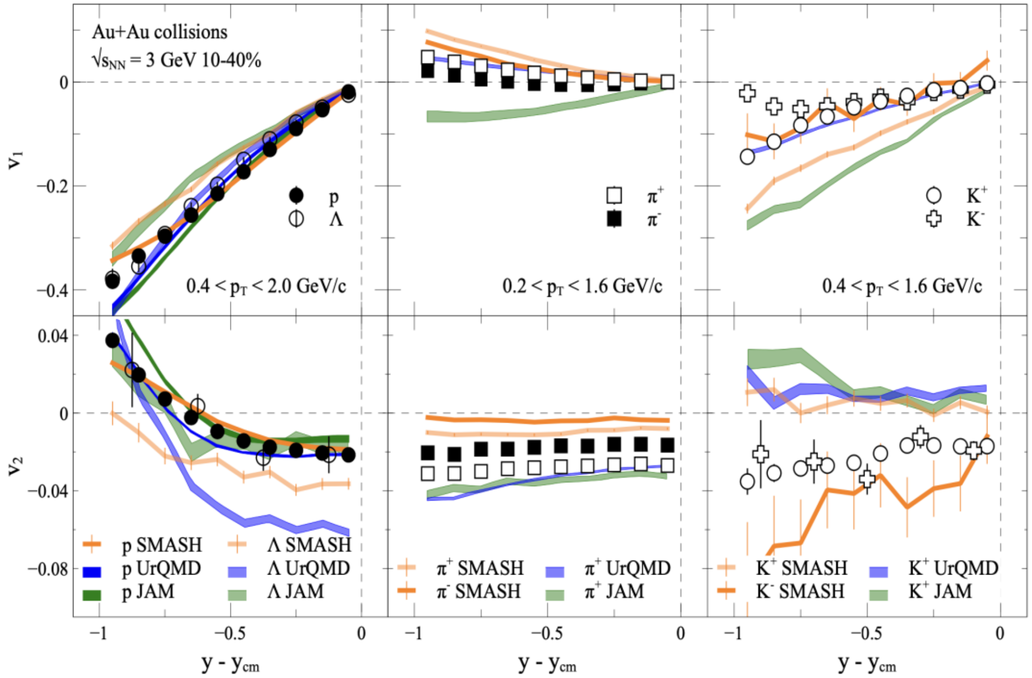


$dN/d\Phi \propto (1 + 2v_1 \cos\Phi + 2v_2 \cos 2\Phi)$

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



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

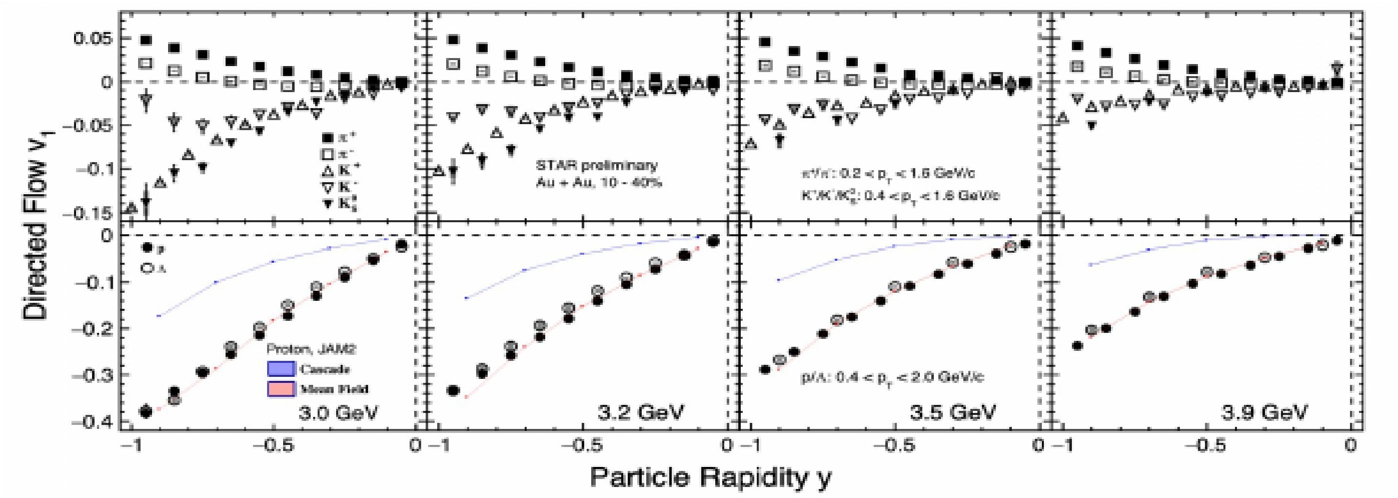


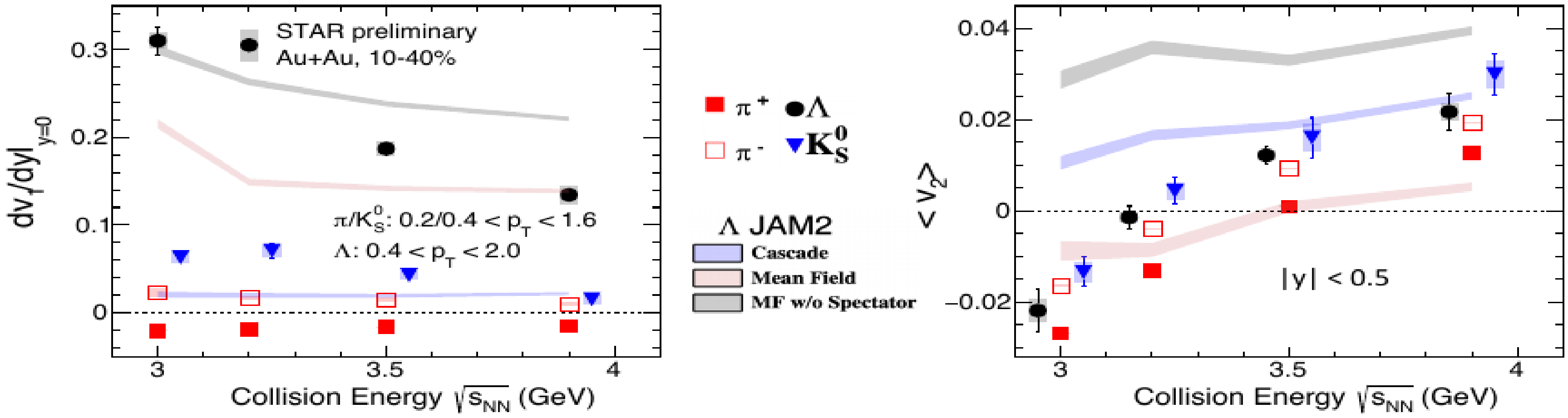
A. Sorensen et. al., arXiv:2301.13253 [nucl-th] (2023)

Models do not describe all particle species equally well

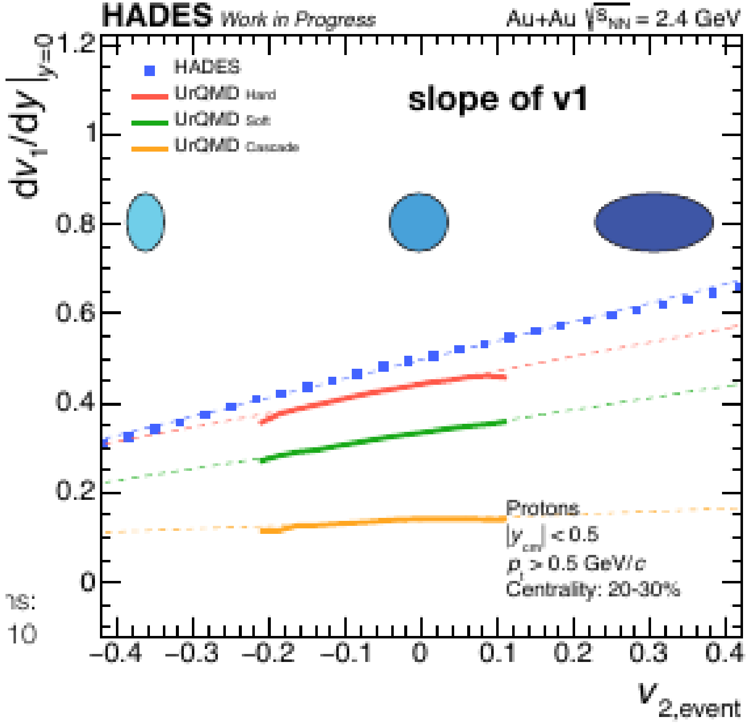
v_1, v_2 of protons are described by JAM, UrQMD (hard EOS) and SMASH (hard EOS with softening at higher densities)

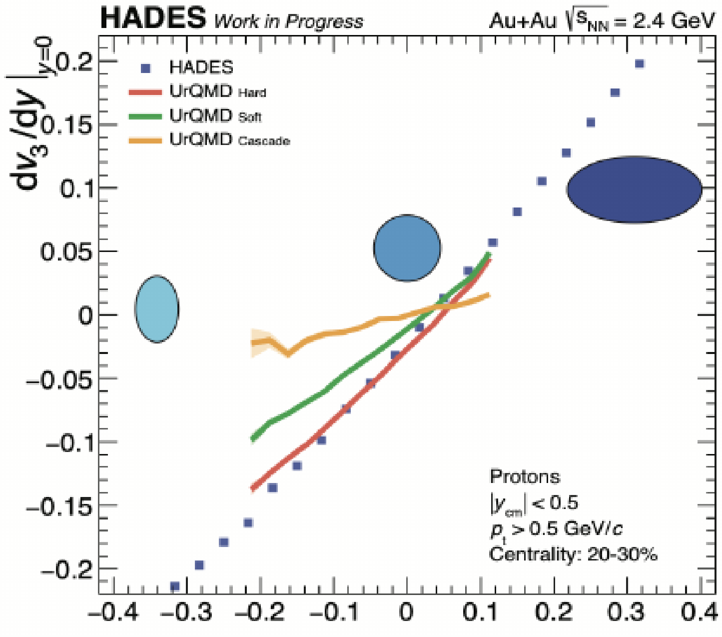
New STAR results from BES – II program were presented at QM2023





New HADES results





Kardan, Blume for HADES. QM23 Poster

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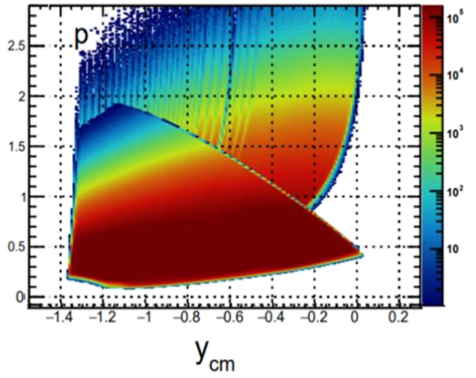
RHIC BES programs

- 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),

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.

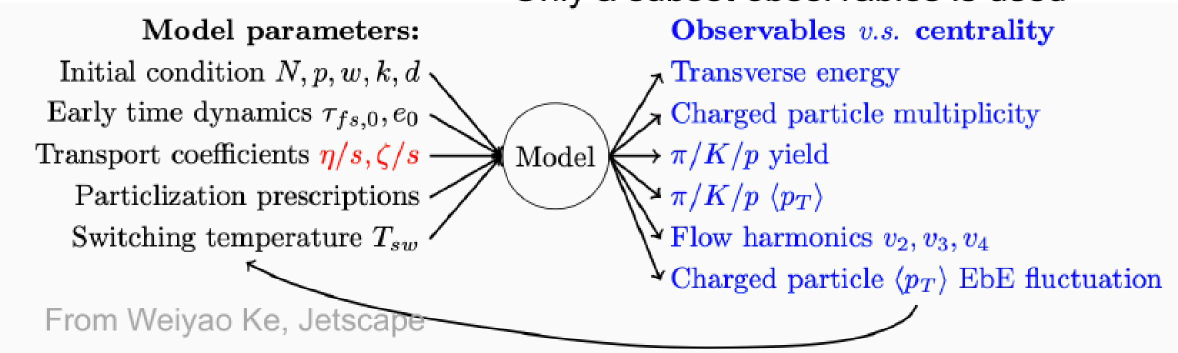
BM@N/NICA energies are very interesting: transition between hadronic and partonic matter?

Back-up slides

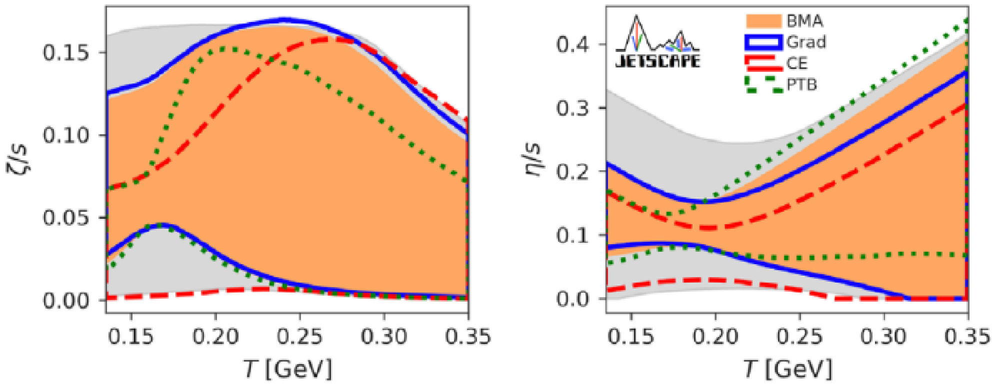
State-of-the-art modeling of HI collisions

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

Only a subset observables is used



- Detailed temperature dependence of viscosity!



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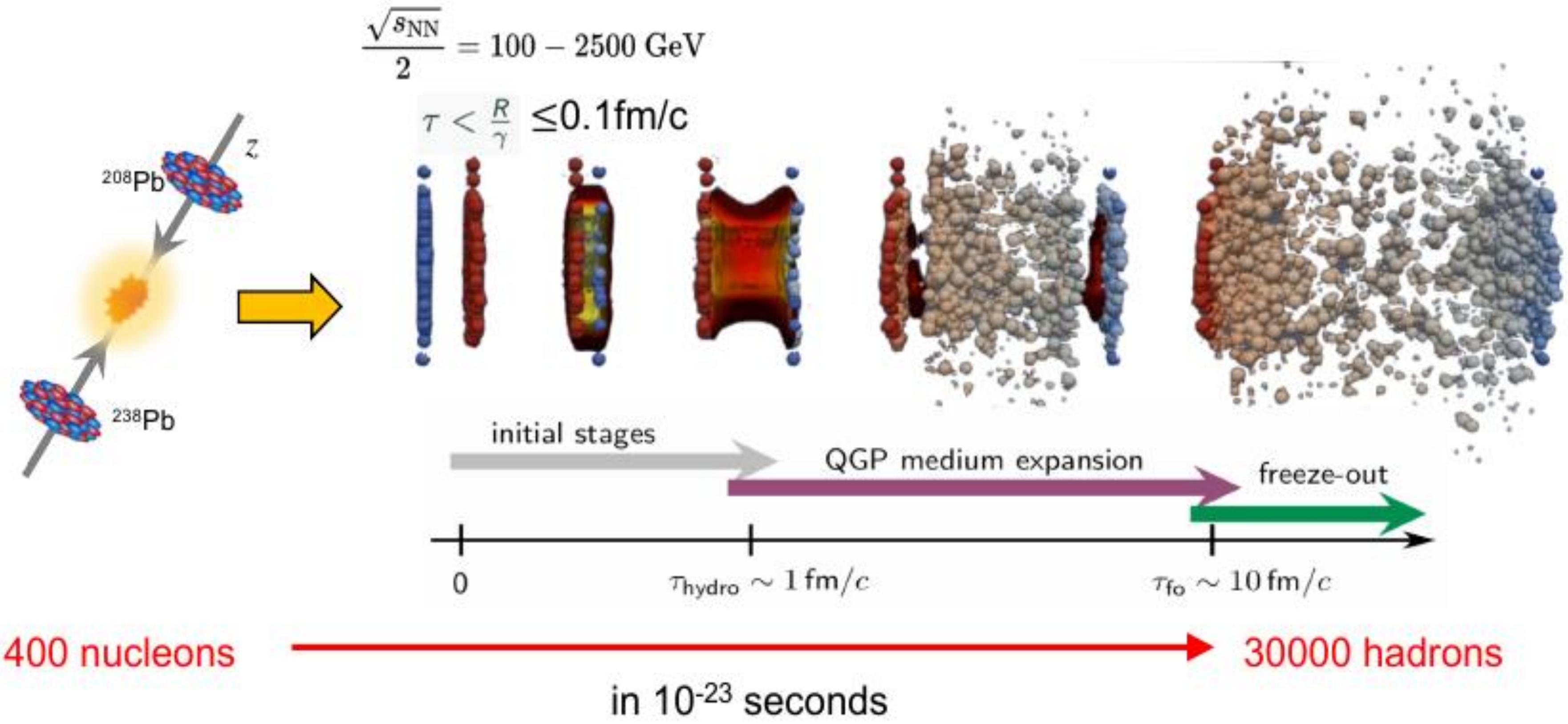
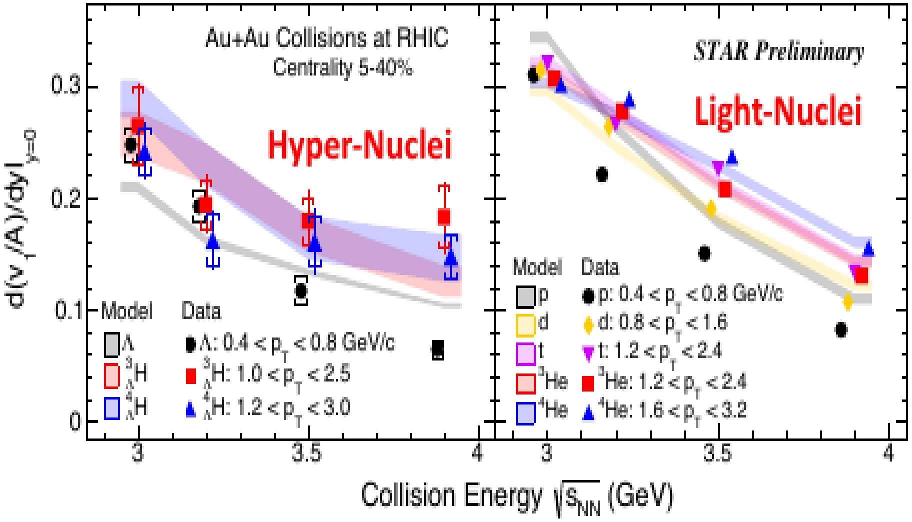
Major uncertainty: initial condition and pre-hydro phase

High-energy heavy ion collision

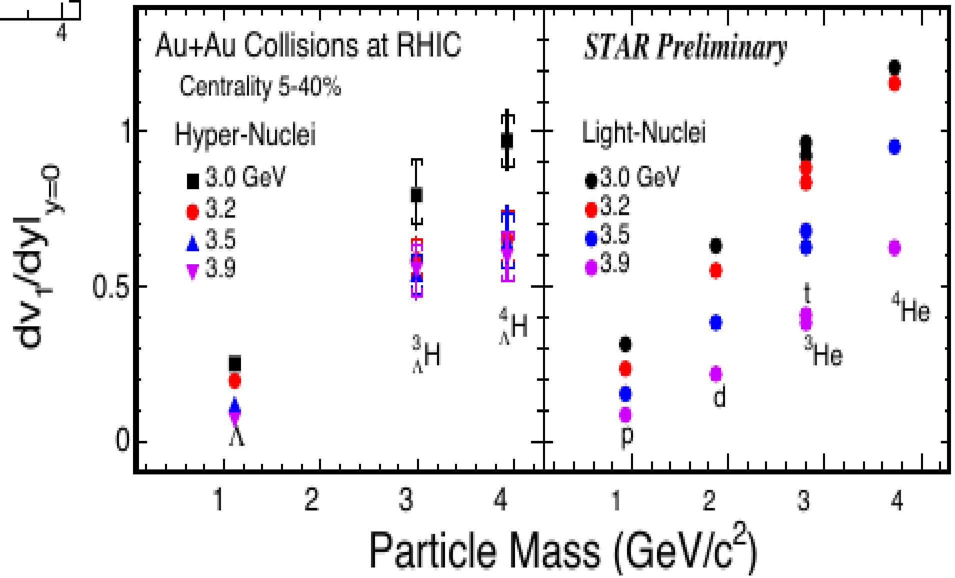


1) Extremely short passing time to take a snap-shot of the nuclear wavefunction in the two nuclei.
2) Large particle production in overlap region means QGP is dense and expand hydrodynamically.



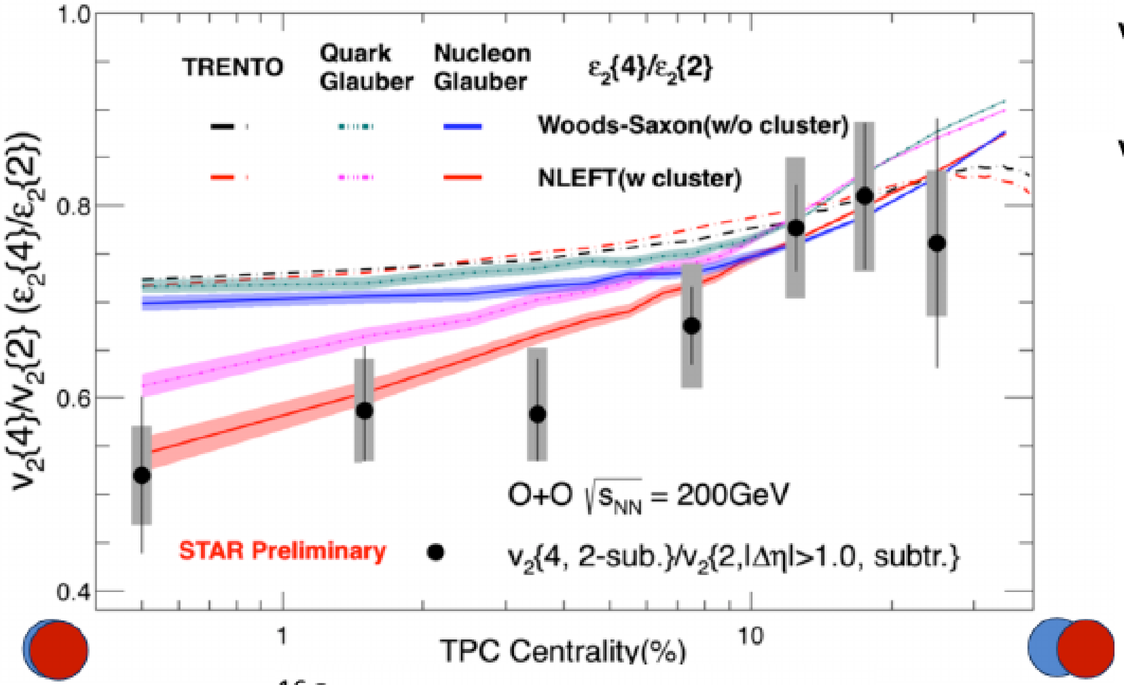
- Hypernuclei at high μ_B can probe Y-N (hyperon-nucleon) interactions
  - Useful for neutron stars!
- **v_1:** Consistent w/Hadronic transport model
  - Decreases with increasing collision energy

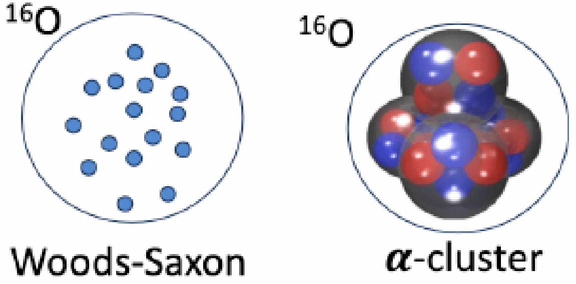
1.B. E. Aboona *et al*., (STAR Collaboration), Phys. Rev. Lett. **130**, 211301(2023)



- 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

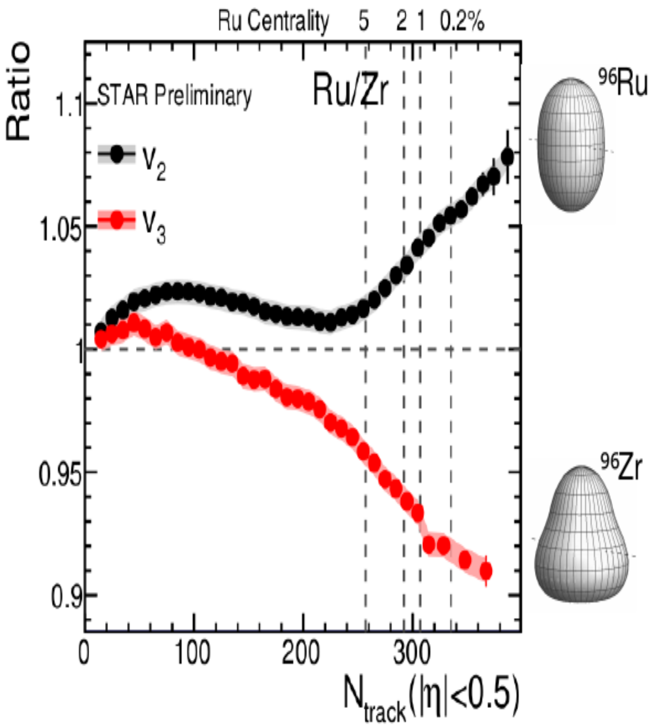
$v_2\{4\}$ - reduced sensitivity to fluctuations

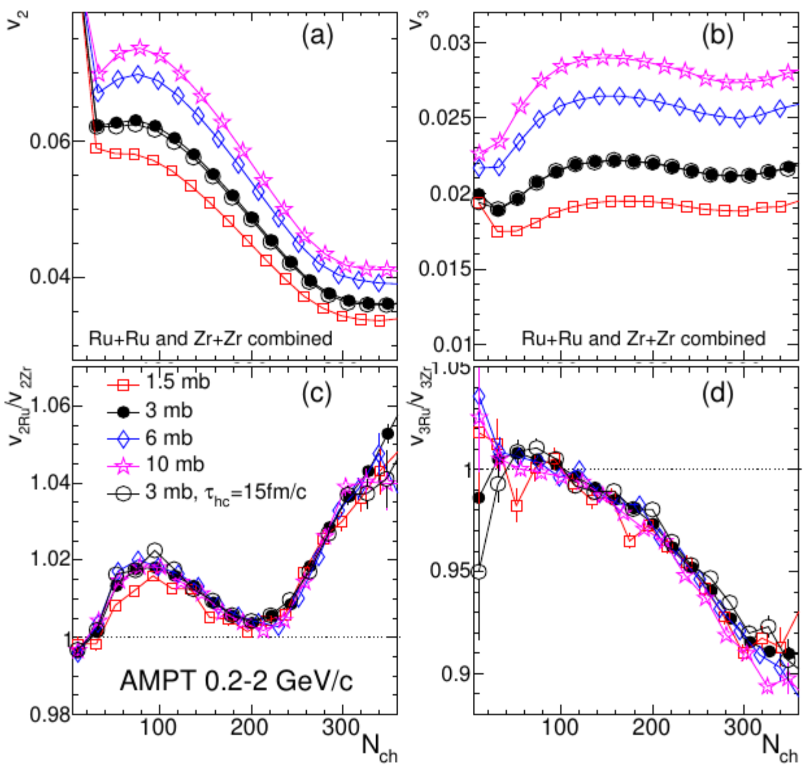
Data:
in central event but fluctuations enhanced, (v_2 reduced overall)

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

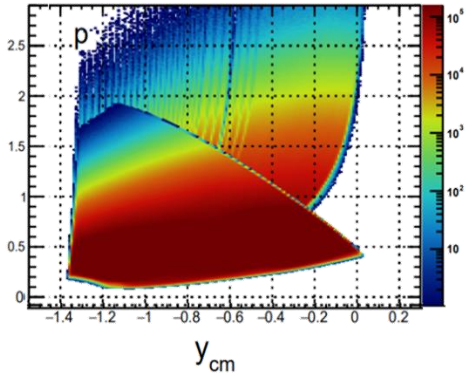
The V_n ratio for isobars – not affected by final state – is a good tool for precision studies of nuclear shapes.

RHIC BES programs

- Data taking by STAR at RHIC: 3 < $\sqrt{s_{NN}}$ < 200 GeV (750 < μ_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

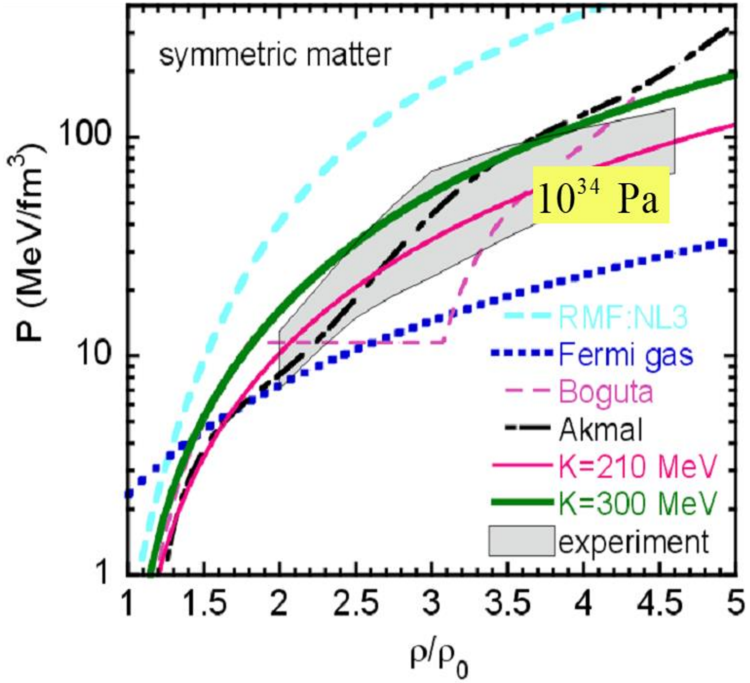
Au+Au @ 3.9 GeV



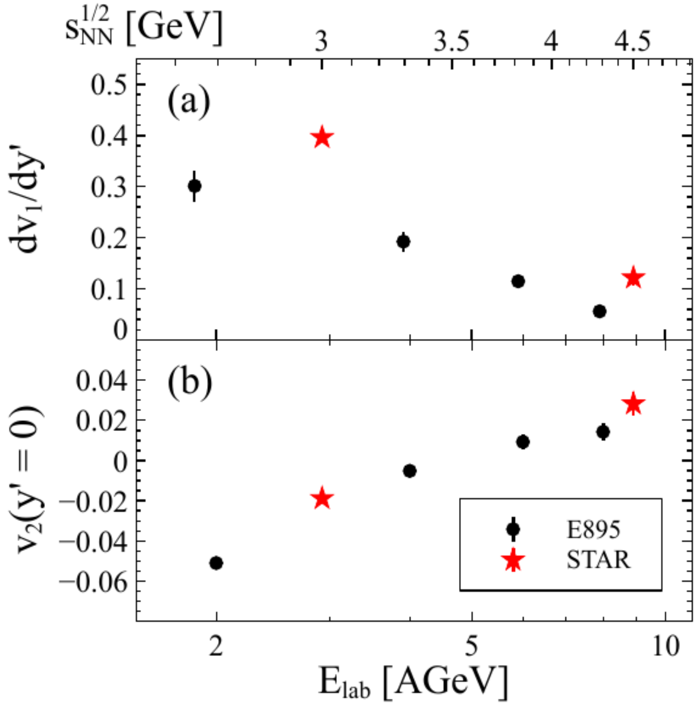
- A very impressive and successful program with many collected datasets, already available and expected results
- Limitations:
  - ✓ Au+Au collisions only
  - ✓ Among the fixed-target runs, only the 3 GeV data have full mid-rapidity coverage for protons (|y| < 0.5),

Flow at AGS: Constraints for the Hadronic EOS

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

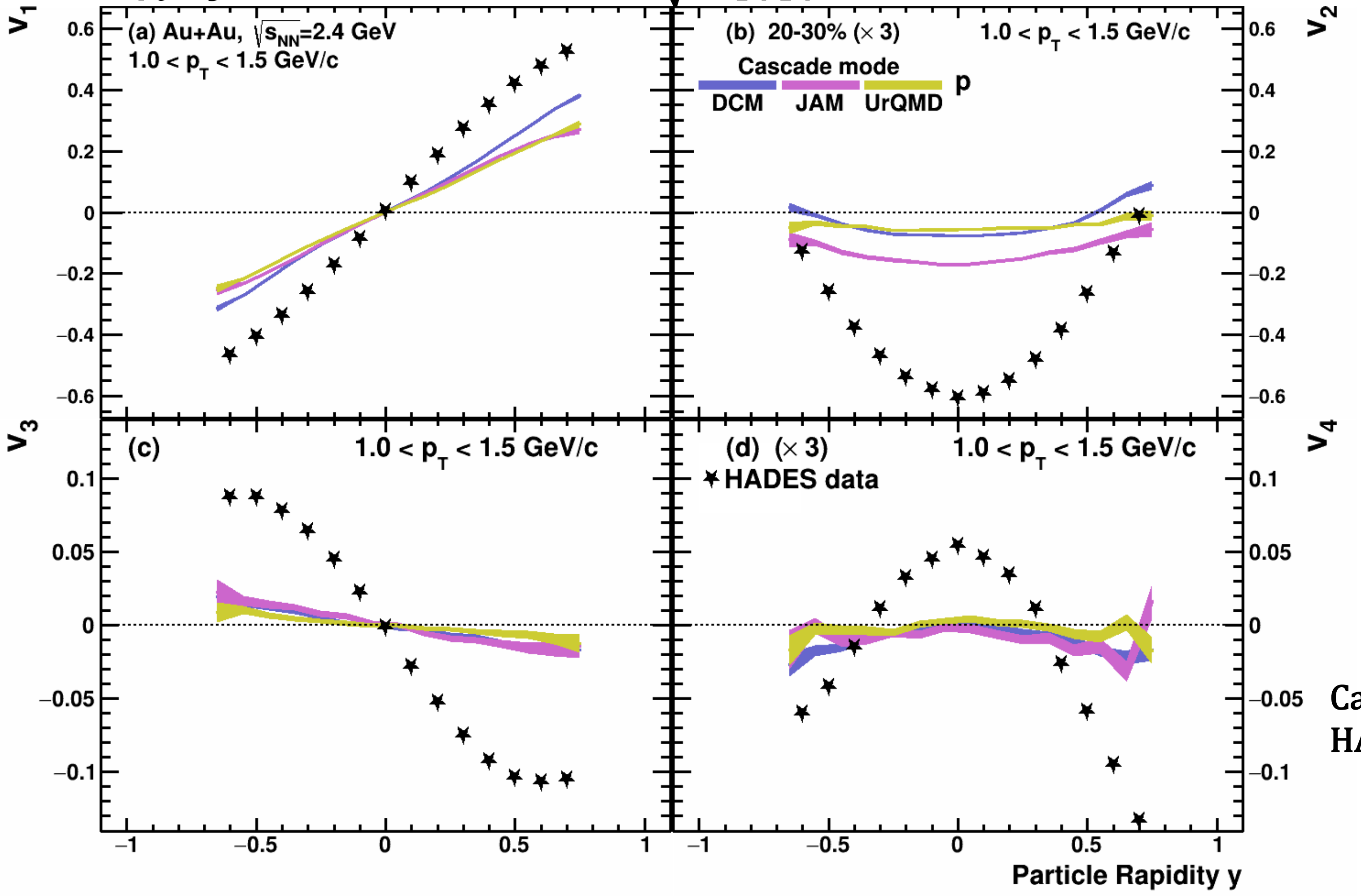


https://arxiv.org/abs/2208.11996



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

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

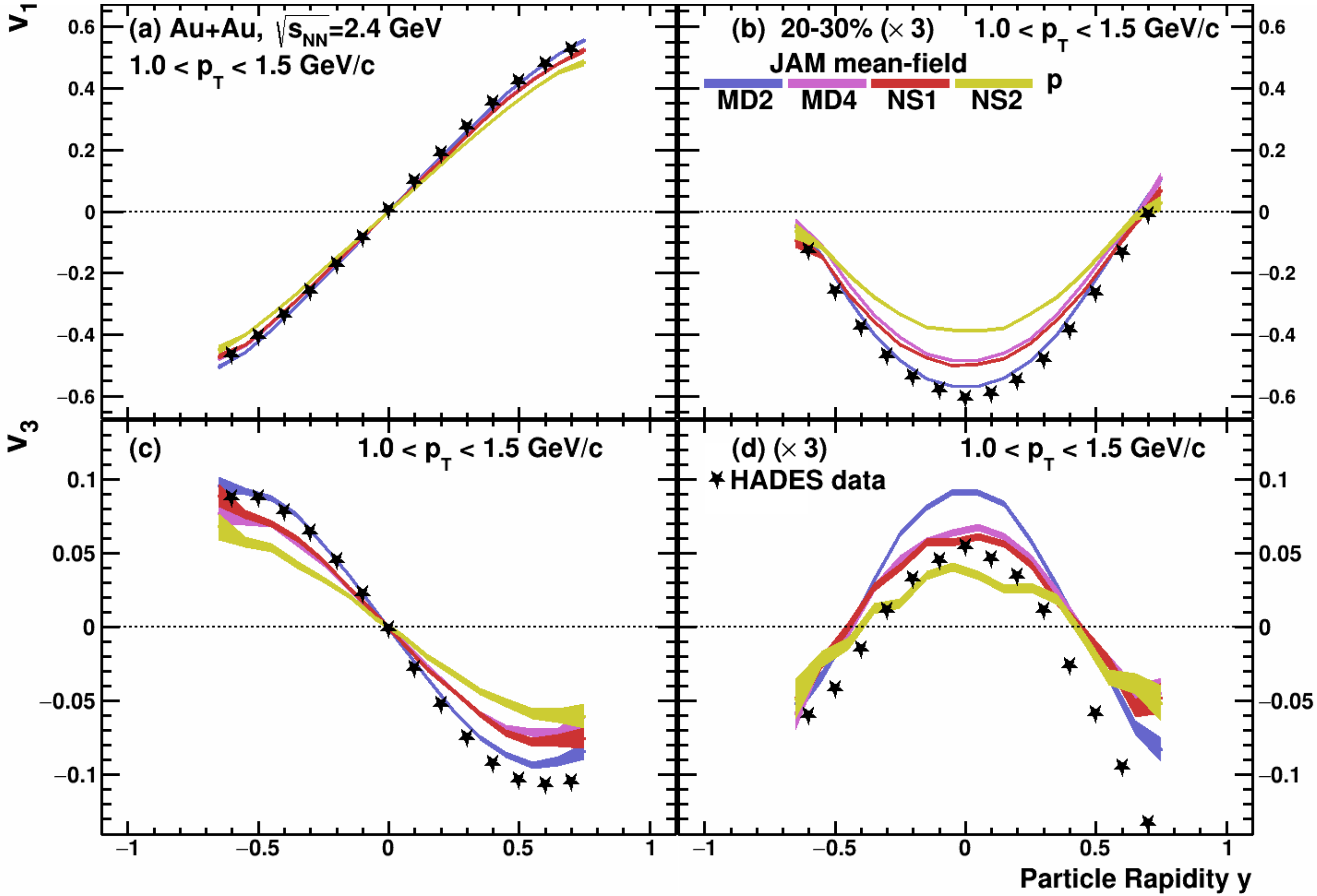


P. Parfenov, Particles 5, no.4, 561-579 (20

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

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

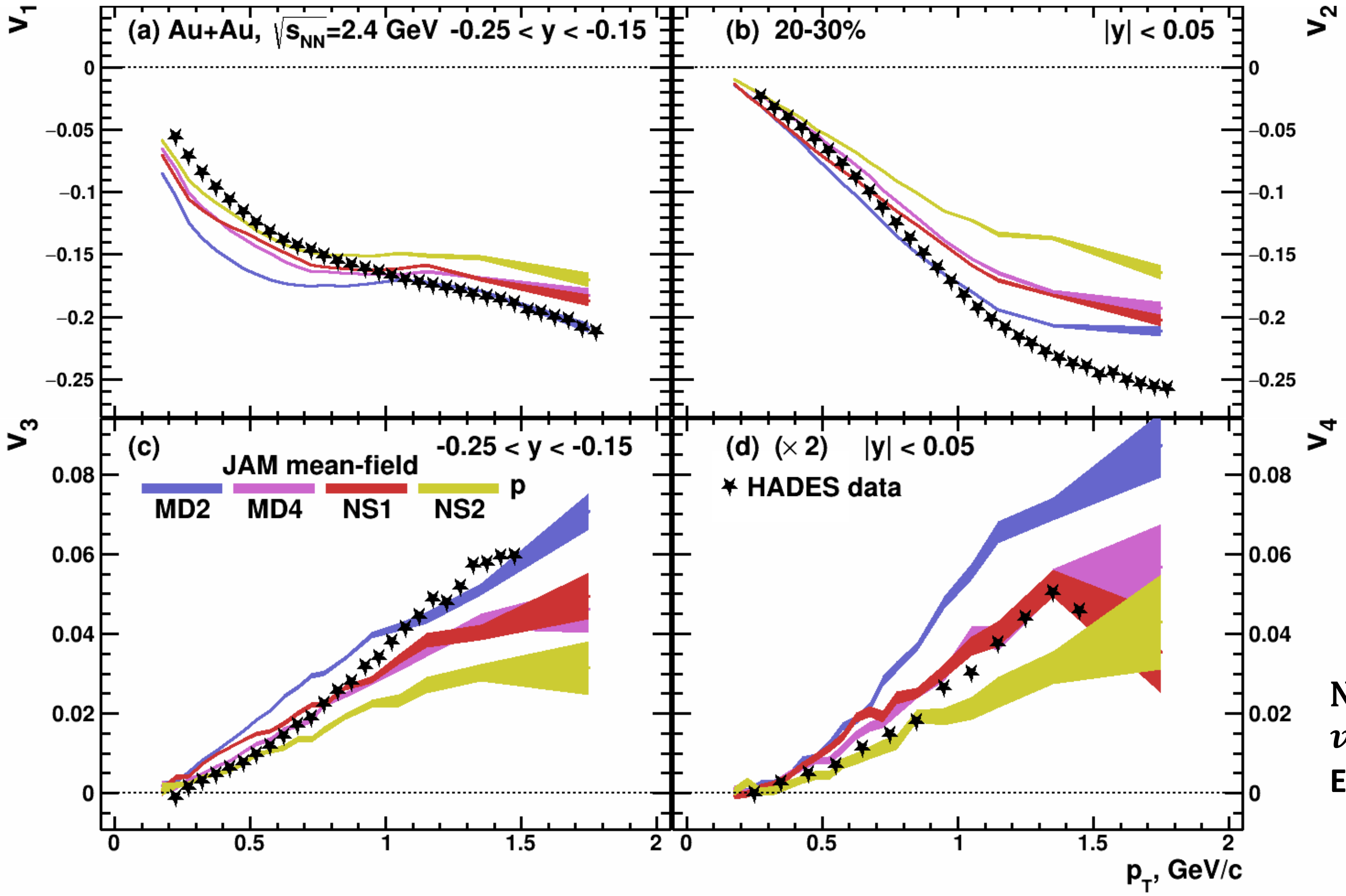


P. Parfenov, Particles 5, no.4, 561-579 (2022)

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

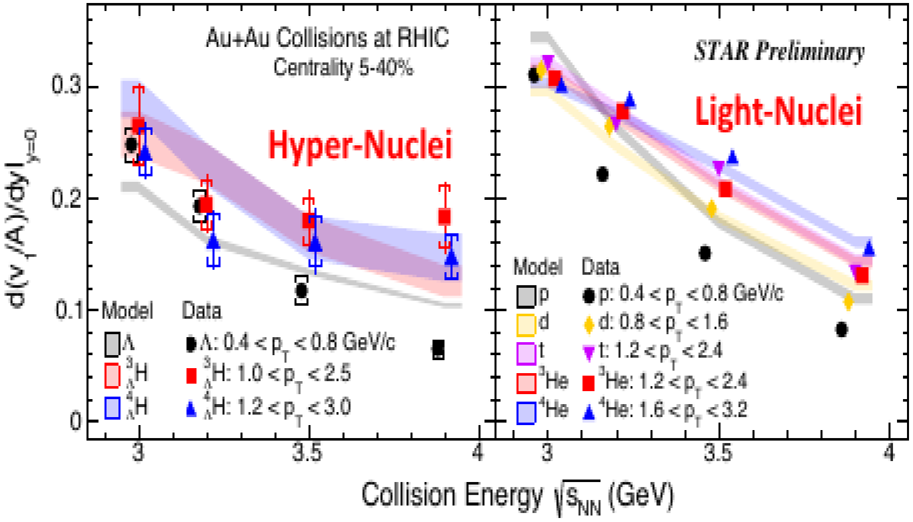


Experimental data points:
Phys. Rev. Lett. **125** (2020) 262301

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

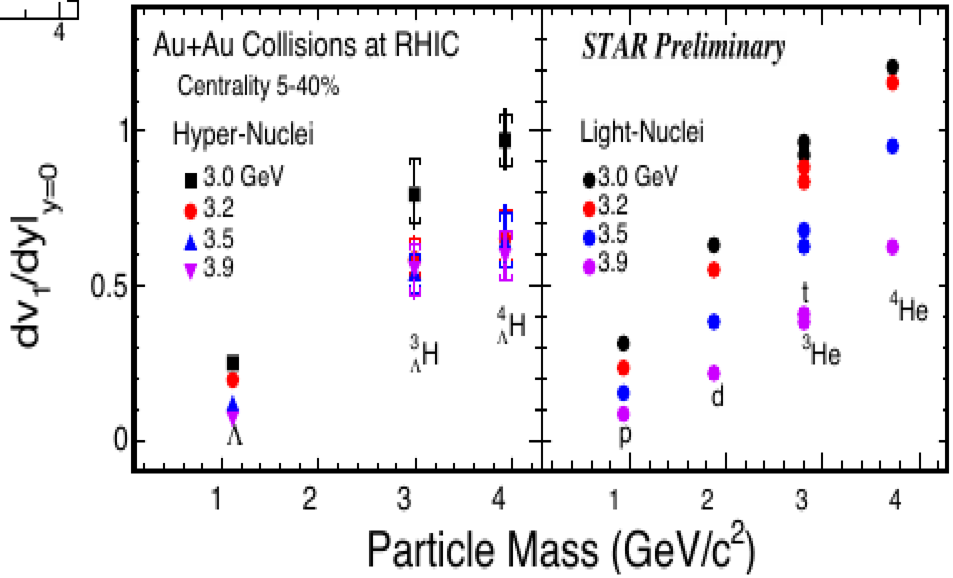
Not a good agreement for $v_n(p_T)$
$v_{3,4}$ are more sensitive to different EOS than v_1

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