Anisotropic Collective Flow at High Baryon Density

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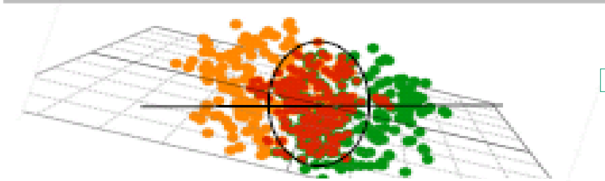
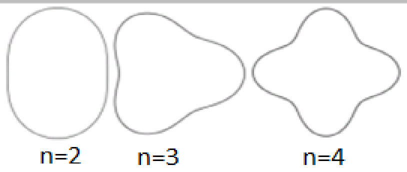
Anisotropic Flow at RHIC-LHC



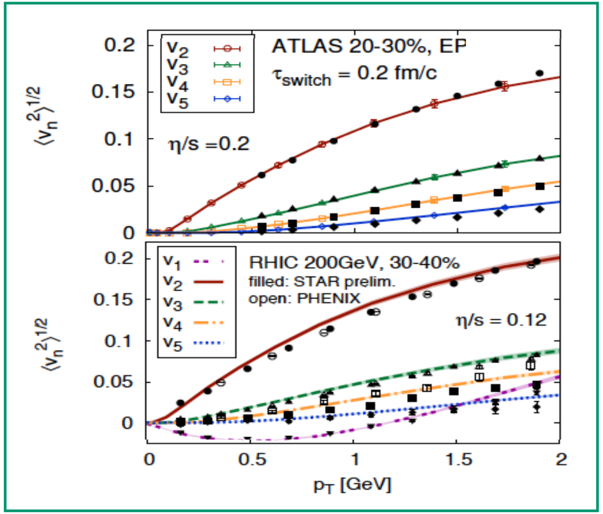


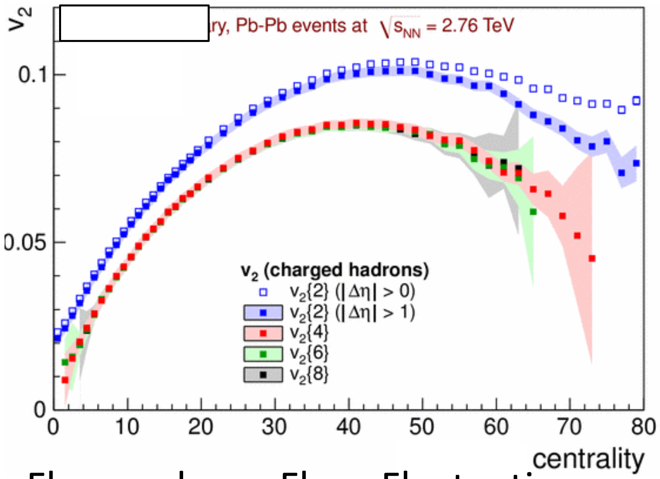
$$\epsilon_n = \sqrt{\frac{\langle r^n \cos n\phi \rangle + \langle r^n \sin n\phi \rangle}{\langle r^n \rangle}}$$

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

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



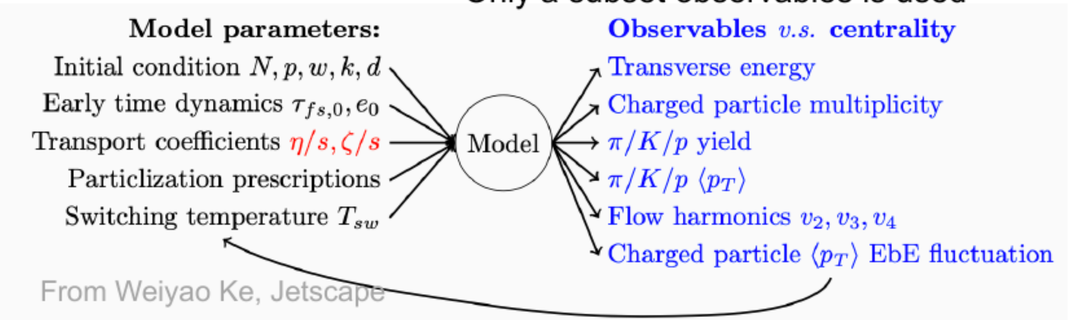


Flow and non-Flow, Fluctuations

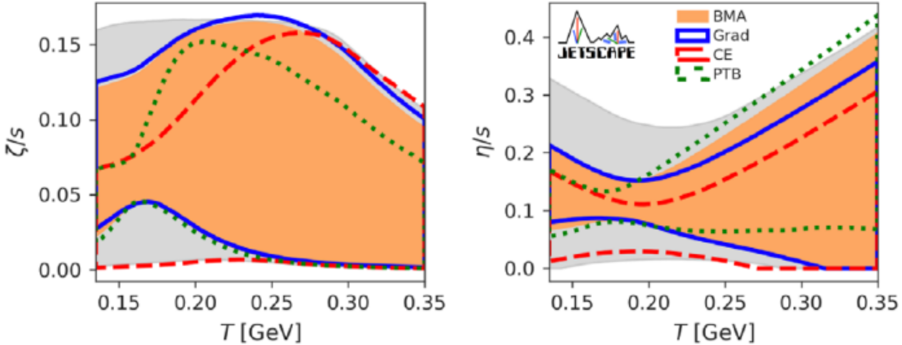
State-of-the-art modeling of HI collisions

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

Only a subset observables is used



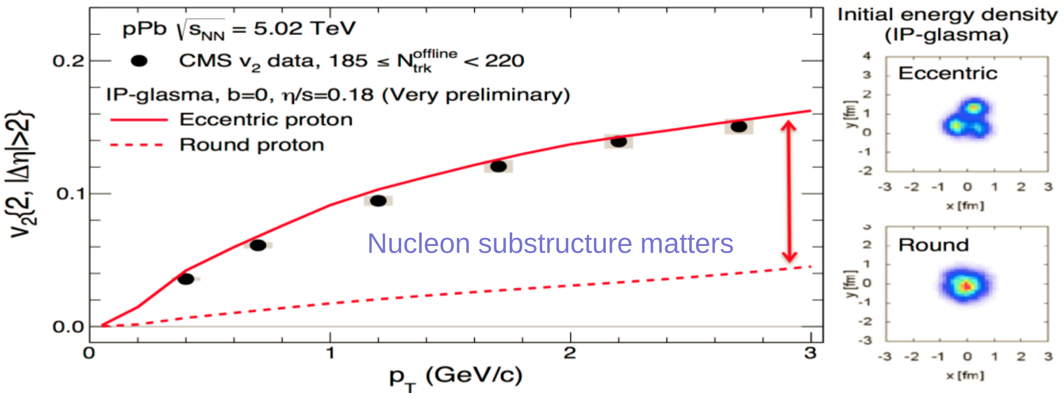
- Detailed temperature dependence of viscosity!



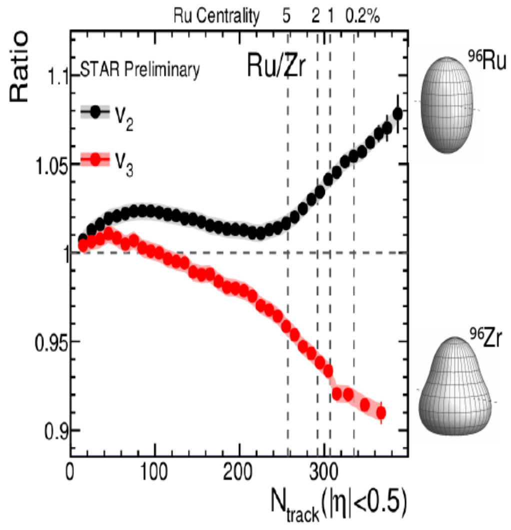
Jetscape PRL.126.242301
Trjactum PRL.126.202301

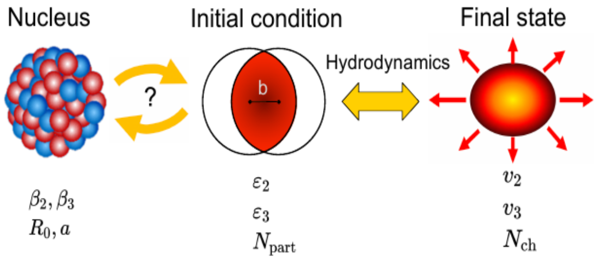
Major uncertainty: initial condition and pre-hydro phase

2011-2020



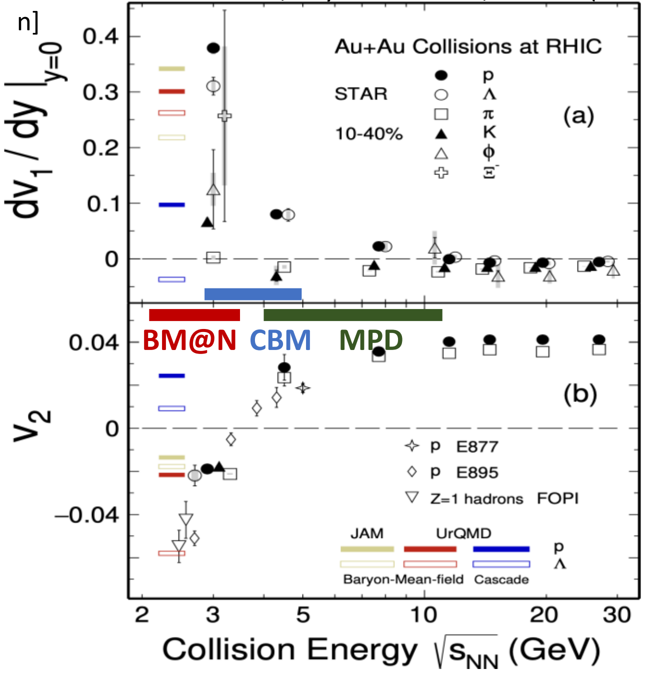
2020-2024

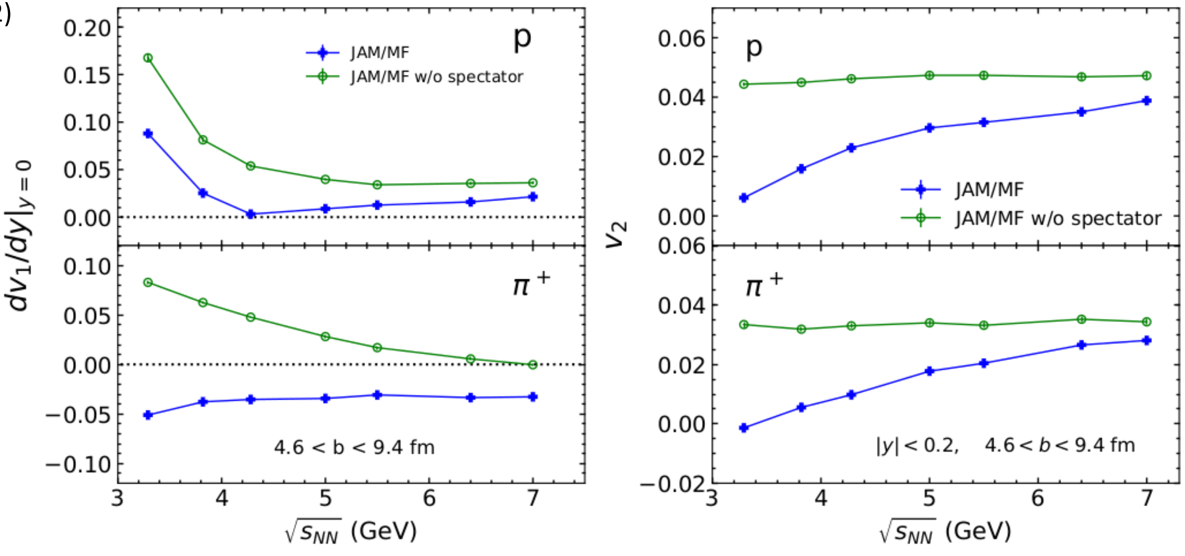




Anisotropic flow in heavy-ion collisions at high baryon density

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





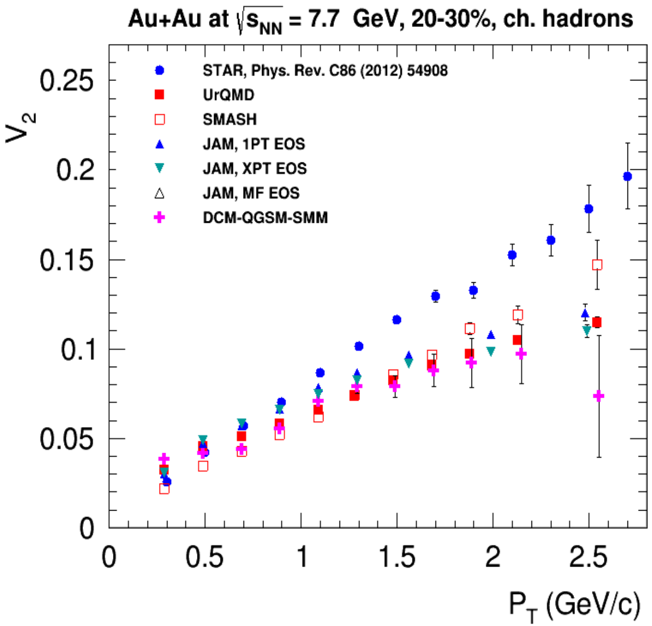
Phys. Rev. C 97, 064913 (2018)

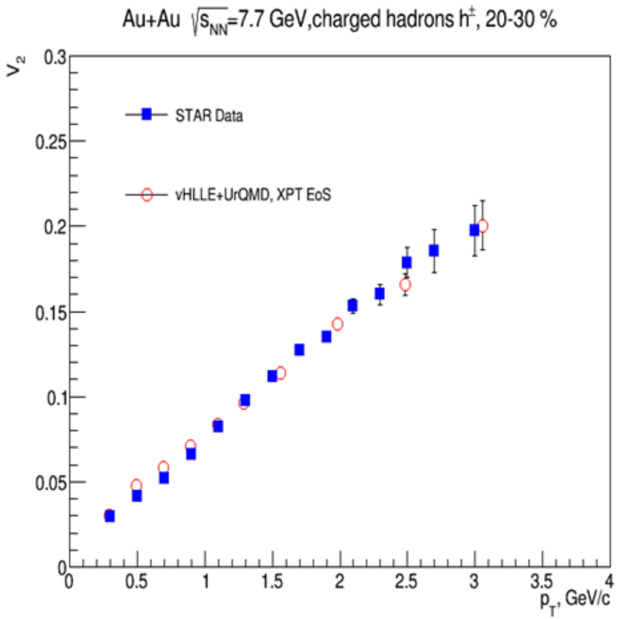
Anisotropic flow at FAIR/NICA energies is a delicate balance between:

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 at NICA energies: Models vs Data comparison





Pure String/Hadronic Cascade models give smaller v_2 signal compared to STAR data for Au+Au $\sqrt{s_{NN}}$=7.7 GeV and above

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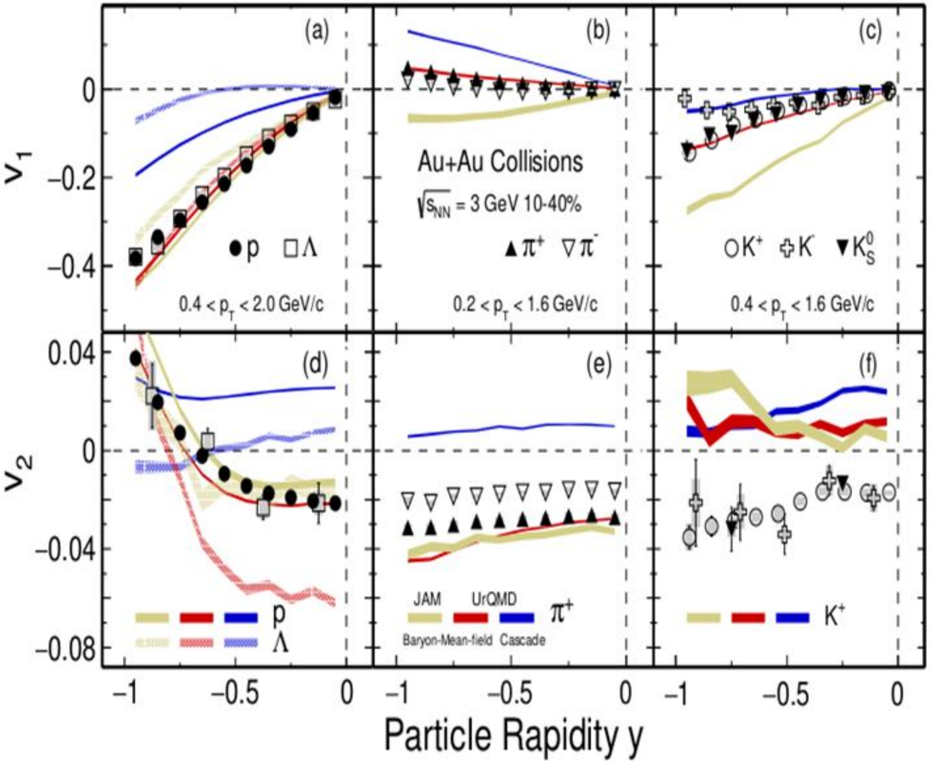
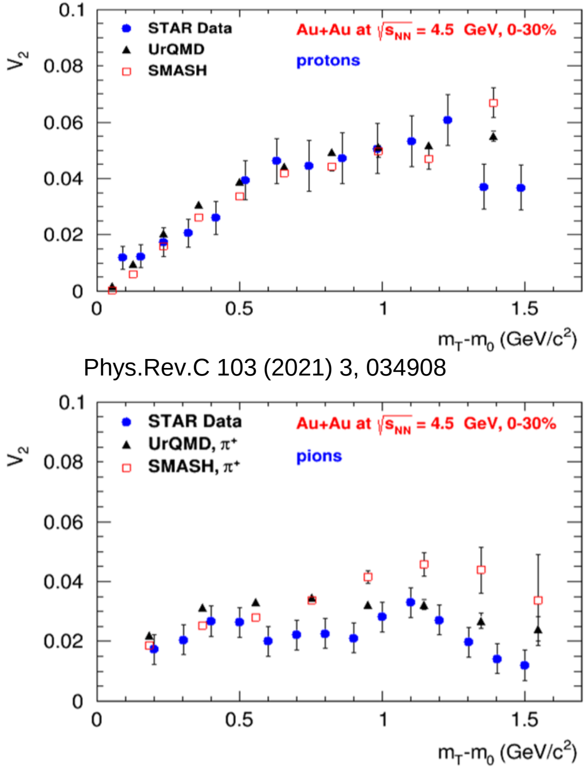
Anisotropic Flow at Nuclotron energies: Models vs Data

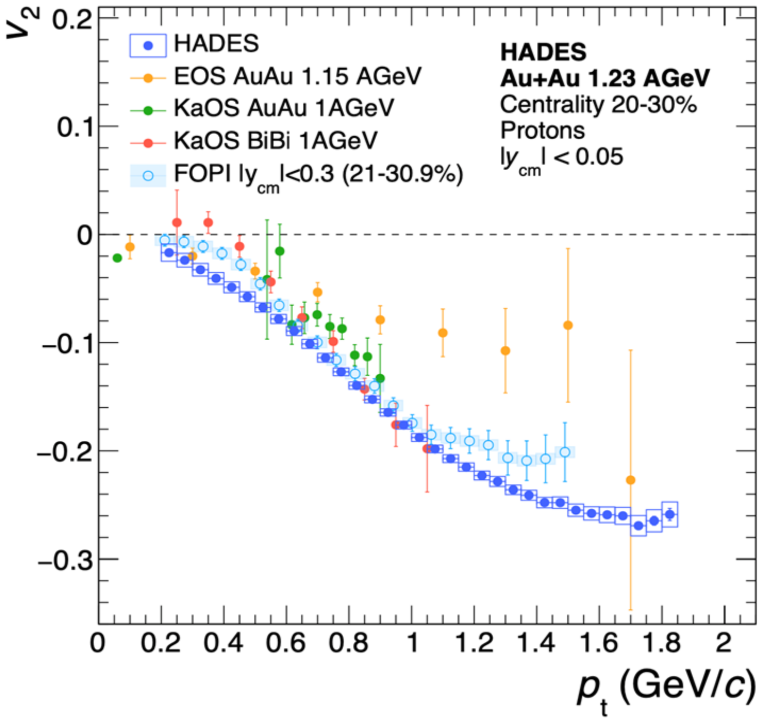


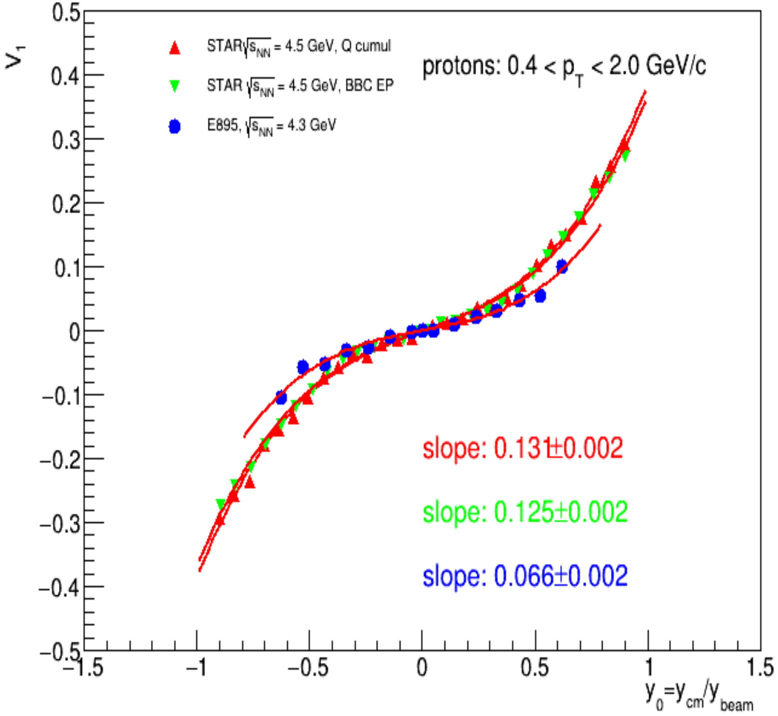


Phys.Rev.C 103 (2021) 3, 034908

at $\sqrt{s_{NN}}$ ~ 3-4.5 GeV pure hadronic models give similar v_2 signal compared to STAR data

The main source of existing systematic errors in v_n measurements





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)

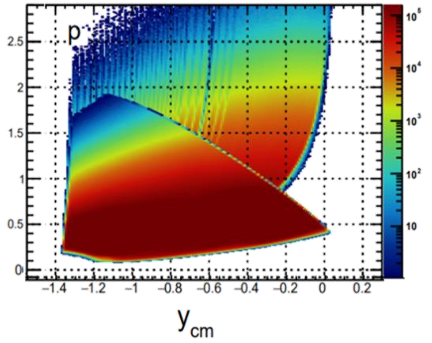
RHIC BES programs

- Data taking by STAR at RHIC: $3 < \sqrt{s_{NN}} < 200$ GeV ($750 < \mu_B < 25$ MeV)

Au+Au Collisions at RHIC

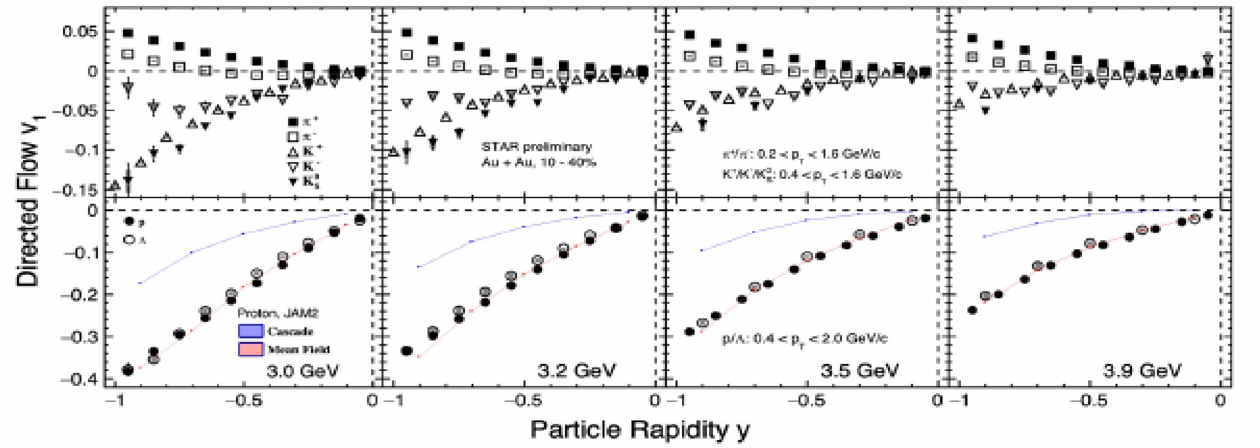
Collider Runs						Fixed-Target Runs					
	$\sqrt{s_{NN}}$ (GeV)	#Events	μ_B	y_{beam}	run		$\sqrt{s_{NN}}$ (GeV)	#Events	μ_B	y_{beam}	run
1	200	380 M	25 MeV	5.3	Run-10, 19	1	13.7 (100)	50 M	280 MeV	-2.69	Run-21
2	62.4	46 M	75 MeV		Run-10	2	11.5 (70)	50 M	320 MeV	-2.51	Run-21
3	54.4	1200 M	85 MeV		Run-17	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

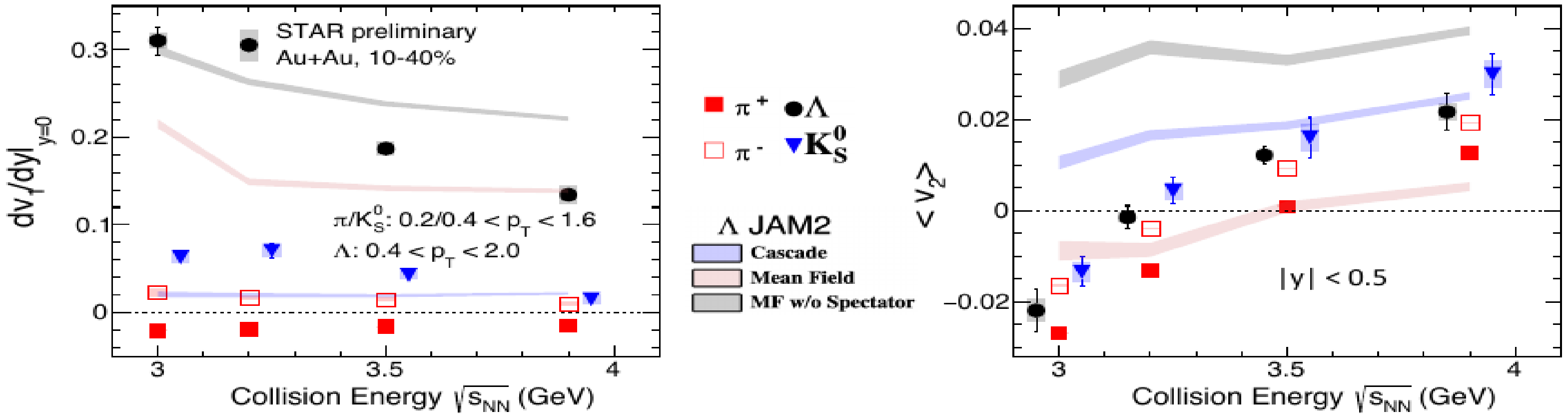
Au+Au @ 3.9 GeV



- 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),

STAR preliminary results from BES – II program





Vn of protons in Au+Au collisions at 2.4 GeV - HADES

Determination of EOS

New level of precision - multi differential

Additional information from higher orders

Models:

JAM 1.9 NS3 (hard EOS, mom.-indep.)

JAM 1.9 MD1 (hard EOS, mom.-dep.)

JAM 1.9 MD4 (soft EOS, mom.dep.)

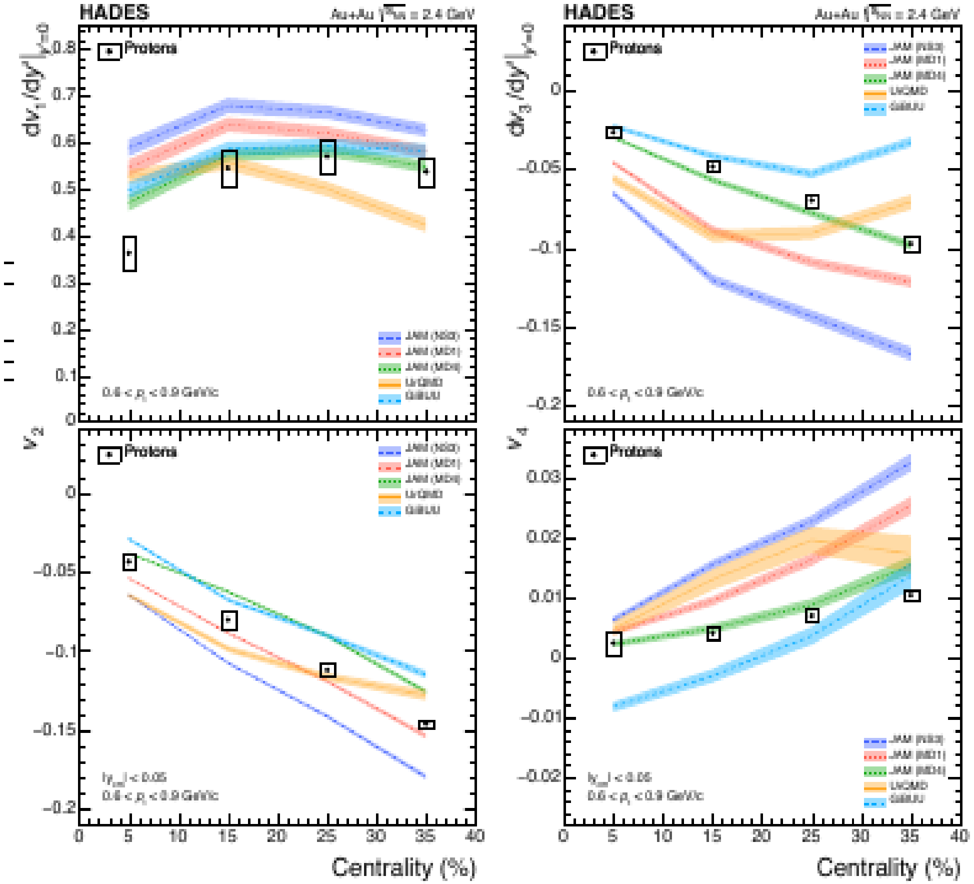
UrQMD 3.4 (hard EOS, mom.-indep.)

GiBUU Skyrme 12 (soft EOS)

Model	EOS	K (MeV)	m^*/m	mom-dep.
JAM 1.90591	NS1	380	0.83	no
	MD1	380	0.65	yes
	MD4	210	0.83	yes
UrQMD 3.4	Hard	380		no
GiBUU 2019 (patch7)	Skyrme 12	240	0.75	no

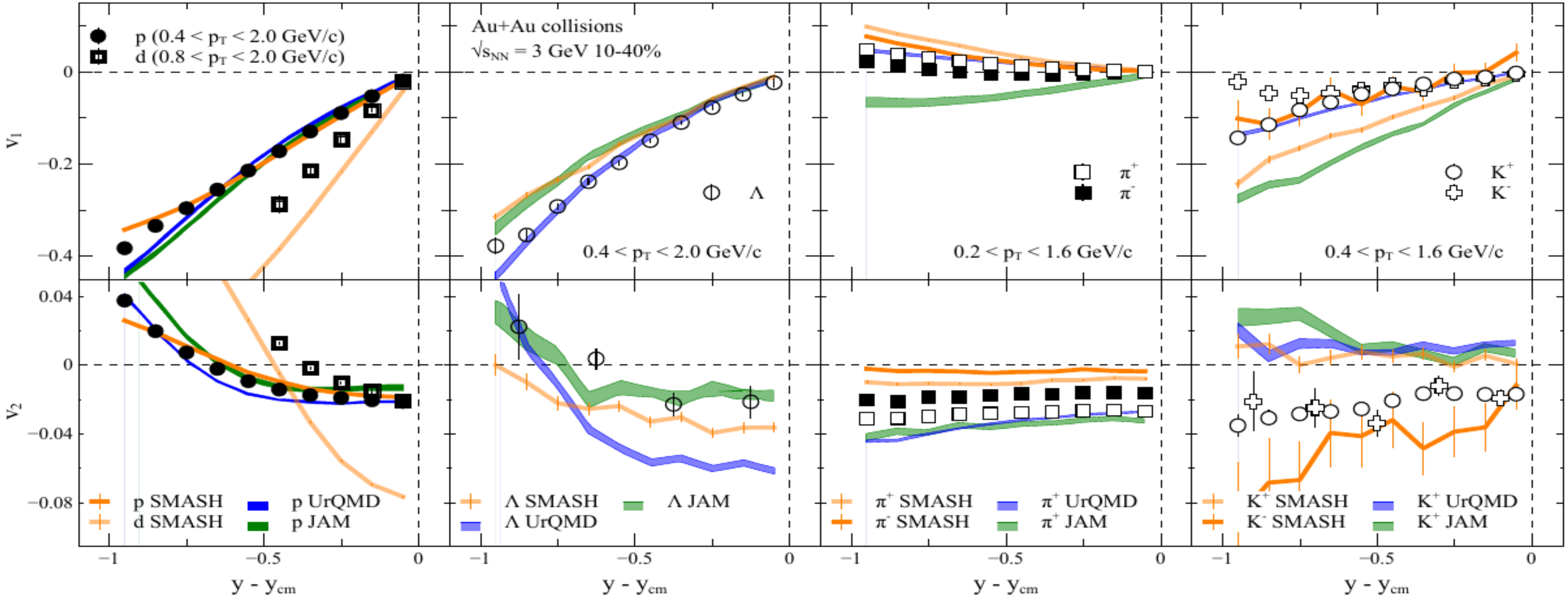
Conclusions

Overall trend reasonably described, but no model works everywhere



Describing proton flow is not enough

Prog.Part.Nucl.Phys. 134 (2024) 104080

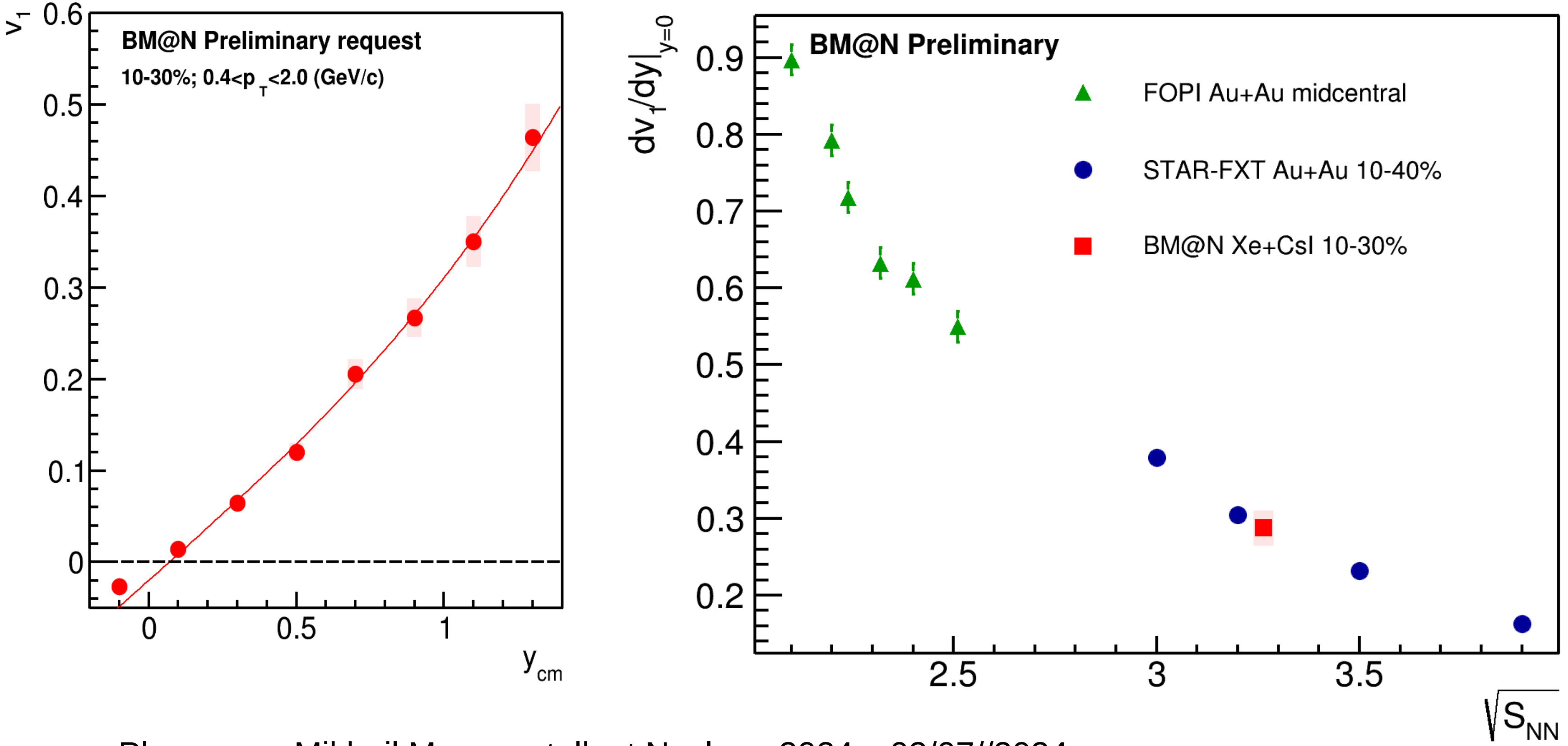


Strange baryons are not well described — the results may depend on:

- nucleon-hyperon and hyperon-hyperon interactions
- in-medium modifications of interactions

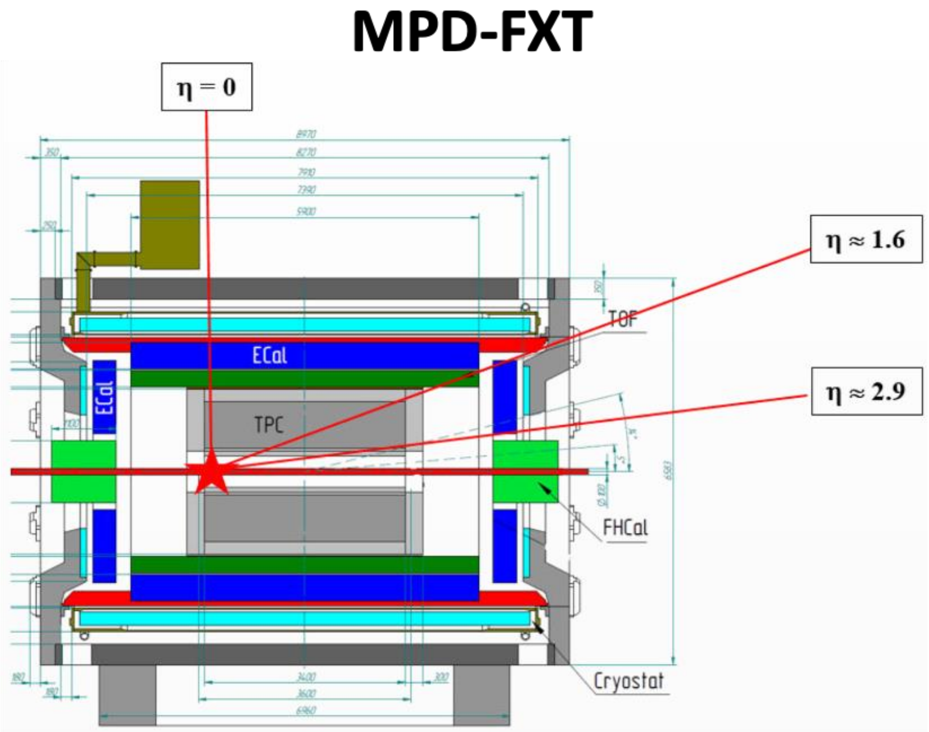
Pions and kaons NOT described!
Not very surprising: UrQMD, JAM, and SMASH don't have mean-fields for mesons

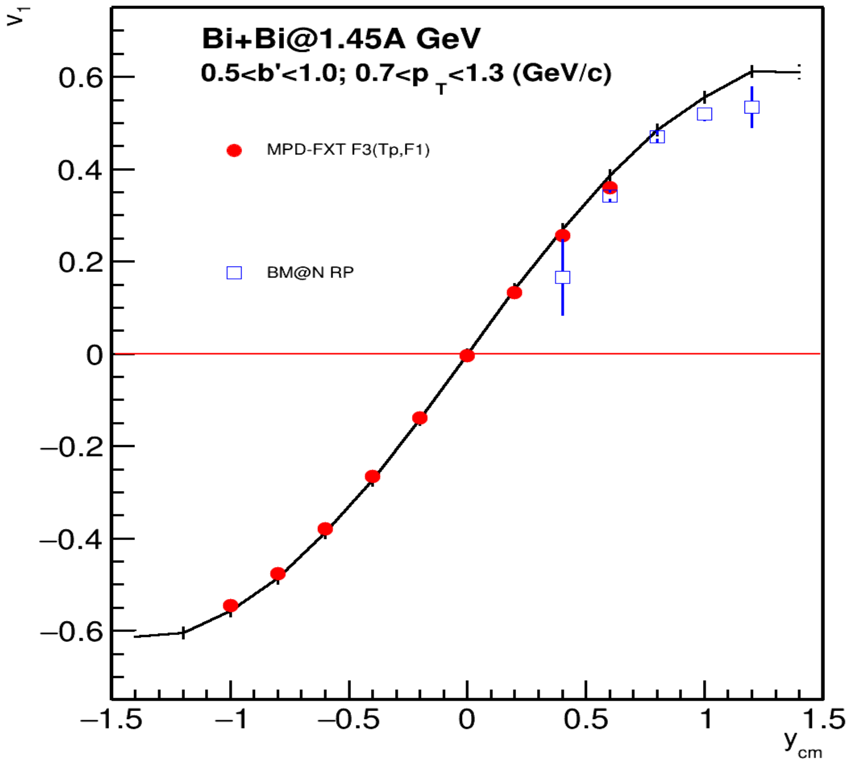
Collision energy dependence of directed flow $dv_1/dy|_{y=0}$



Please see Mikhail Mamaev talk at Nucleus-2024 – 03/07//2024

MPD in Fixed-Target Mode (FXT) vs BM@N





Please see Pater Parfenov talk at Nucleus-2024 – 02/07//2024

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.
- **v_n at NICA energies shows strong energy dependence:**
  - At $\sqrt{s_{NN}}$=4.5 GeV v_2 from UrQMD, SMASH, JAM are in a good agreement with the experimental data
  - At $\sqrt{s_{NN}}\geq$7.7 GeV UrQMD, SMASH underestimate v_2 – need hybrid models with QGP phase
- **Feasibility study for anisotropic flow in MPD/MPD FXT/BM@N:**
- Programs for flow analysis are available for MPD/BM@N collaboration – first flow results from BM@N will come very soon

Backup