System Size Scan at NICA Energies

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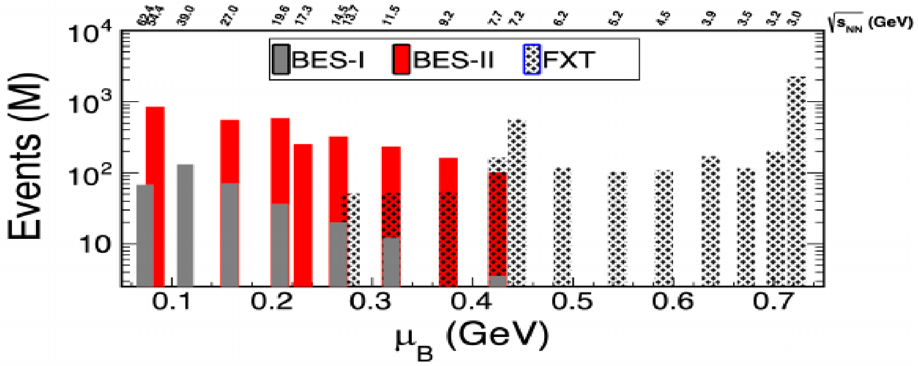
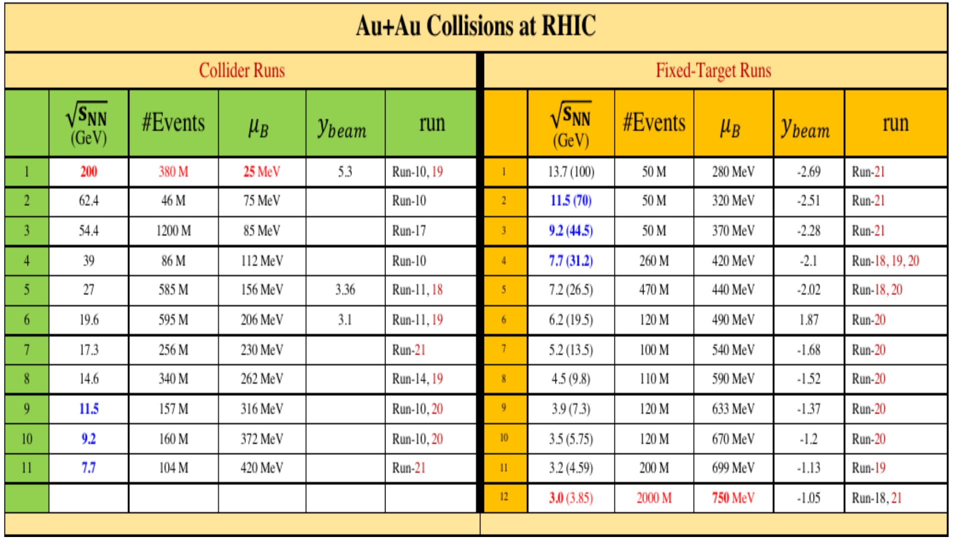
Beam Energy Scan programs

STAR at RHIC: 3 < $\sqrt{s_{NN}}$ < 200 GeV (750 < μ_B < 25 MeV)

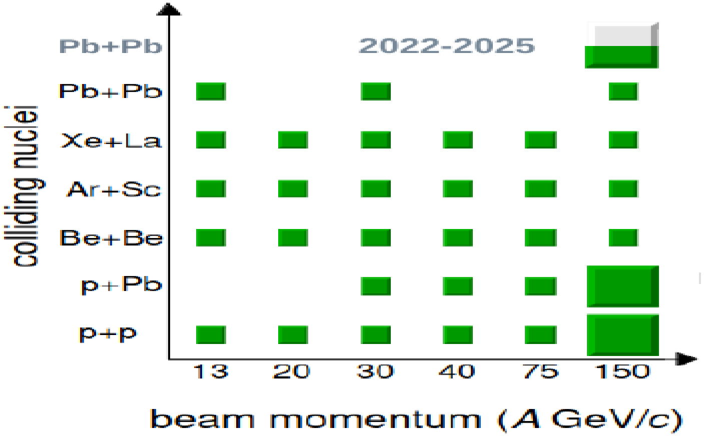


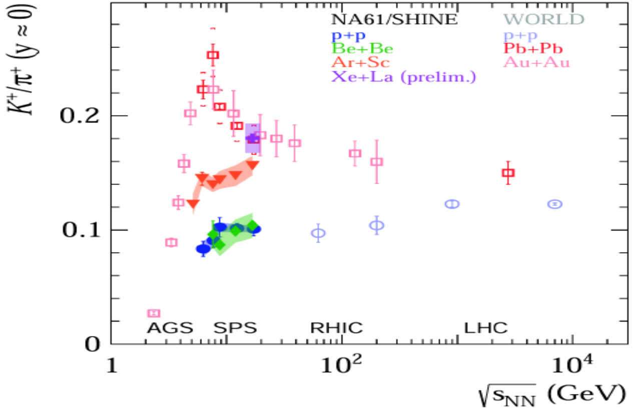


Au+Au Collisions at RHIC

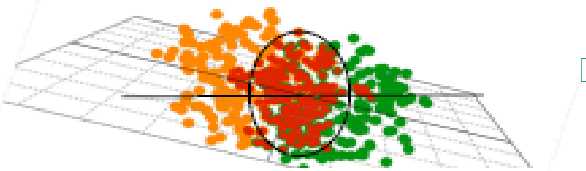
Collider Runs						Fixed-Target Runs					
	$\sqrt{s_{NN}}$ (GeV)	#Events	μ_B	y_{beam}	run		$\sqrt{s_{NN}}$ (GeV)	#Events	μ_B	y_{beam}	run
1	**200**	380 M	**25** MeV	5.3	Run-10, 19	1	13.7 (100)	50 M	280 MeV	-2.69	Run-21
2	62.4	46 M	75 MeV		Run-10	2	**11.5 (70)**	50 M	320 MeV	-2.51	Run-21
3	54.4	1200 M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

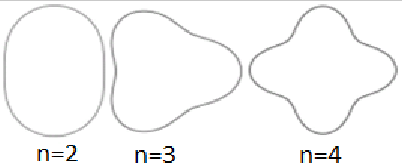
NA61SINE at SPS: 5.1 < $\sqrt{s_{NN}}$ < 17 (27) GeV





Anisotropic Flow at RHIC-LHC



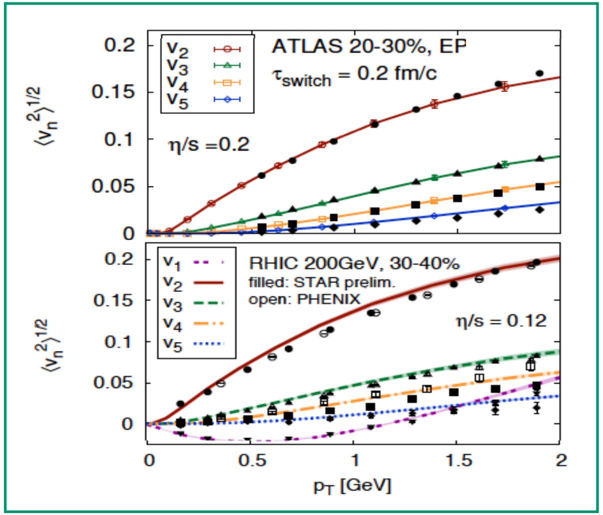


$$\epsilon_n = \sqrt{\frac{\langle r^n \cos n\phi\rangle + \langle r^n \sin n\phi\rangle}{\langle r^n\rangle}}$$

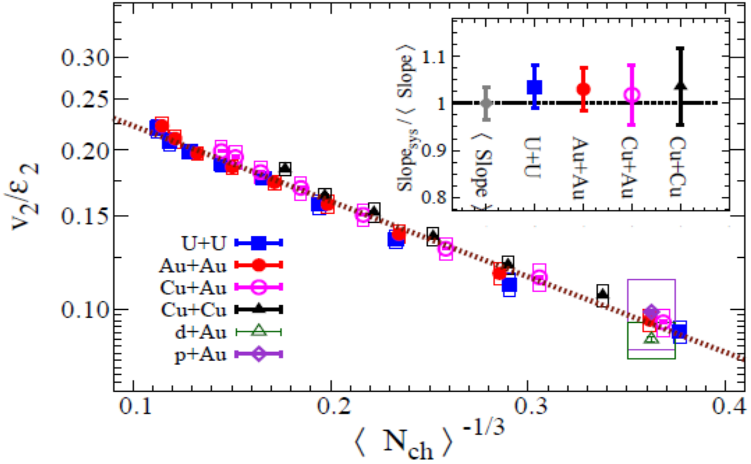
$$\frac{dN}{d\phi} \propto \left(1+2\sum_{n=1} v_n \cos\left[n\left(\phi-\Psi_n\right)\right]\right)$$

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

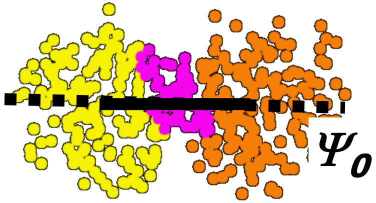


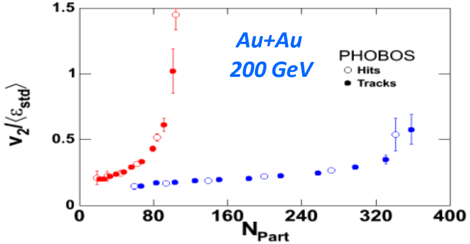
STAR, Phys. Rev. Lett. 122 (2019) 172301



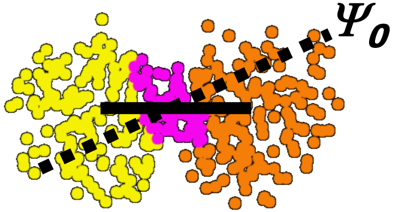
System size scan at top RHIC energy

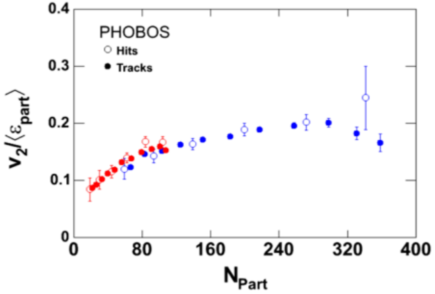
2001-2005 $$\varepsilon_{\rm std} = \frac{\sigma_y^2-\sigma_x^2}{\sigma_x^2+\sigma_y^2}$$



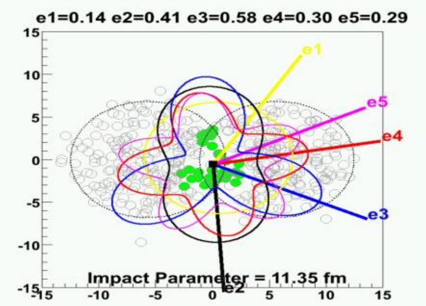


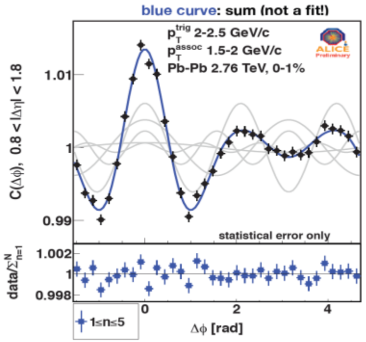
2005-2011 $$\langle\epsilon_{\rm part}\rangle = \frac{\sqrt{(\sigma_y^2-\sigma_x^2)^2+4\sigma_{xy}^2}}{(\sigma_y^2+\sigma_x^2)}$$





2011-2012 $$\epsilon_n = \sqrt{\frac{\langle r^n\cos n\phi\rangle+\langle r^n\sin n\phi\rangle}{\langle r^n\rangle}}$$



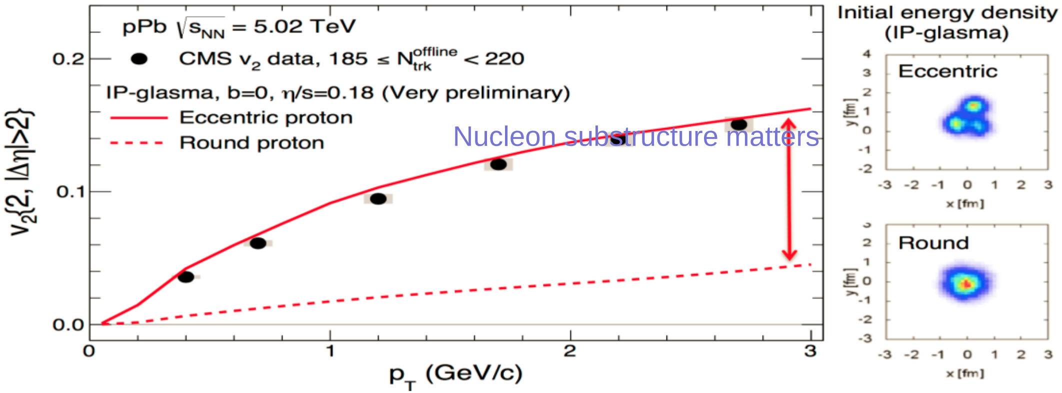


For "lumpy" *profile* $\varphi \neq \varphi + \pi$

Odd harmonics ≠ 0

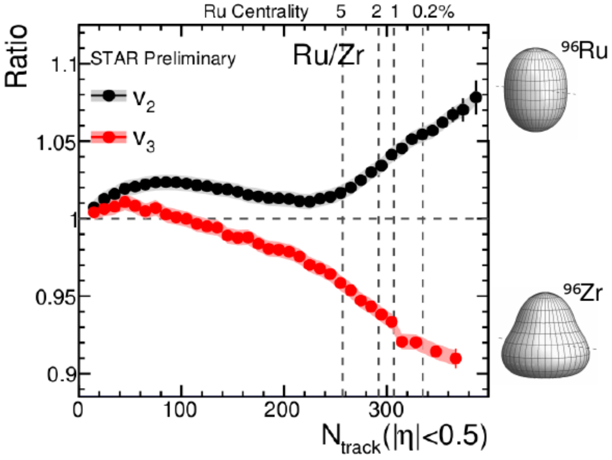
System size scan at top RHIC energy

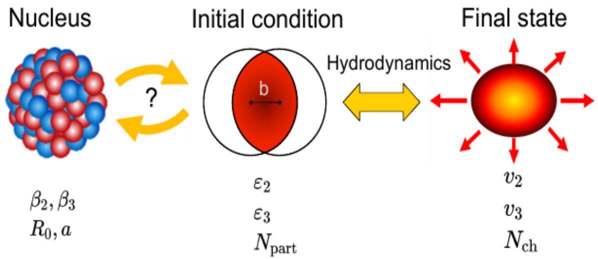
2011-2020



Nucleon substructure matters

2020-2024

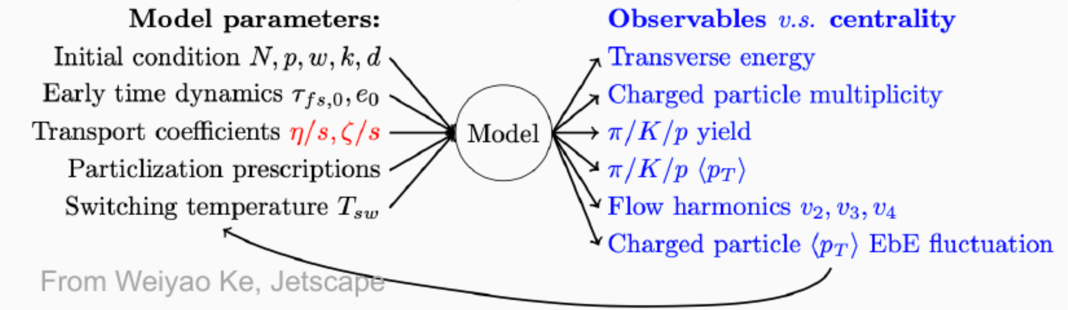




State-of-the-art modeling of HI collisions

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

Only a subset observables is used



Model parameters:

Initial condition N, p, w, k, d

Early time dynamics $\tau_{fs,0}, e_0$

Transport coefficients $\eta/s, \zeta/s$

Particlization prescriptions

Switching temperature T_{sw}

Model

Observables *v.s.* centrality

Transverse energy

Charged particle multiplicity

$\pi/K/p$ yield

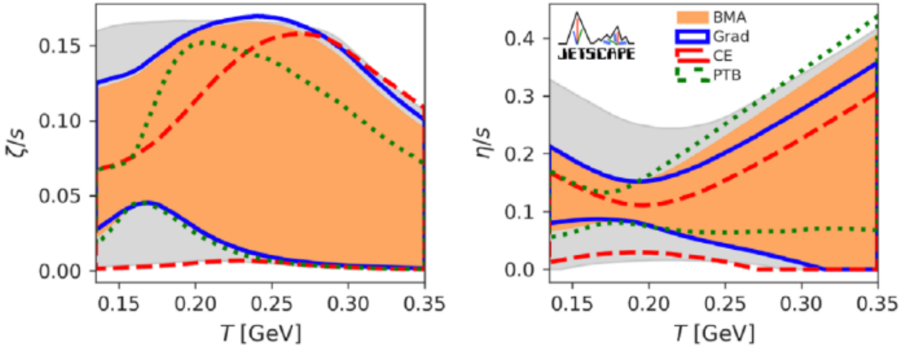
$\pi/K/p$ $\langle p_T \rangle$

Flow harmonics v_2, v_3, v_4

Charged particle $\langle p_T \rangle$ EbE fluctuation

From Weiyao Ke, Jetscape

- Detailed temperature dependence of viscosity!

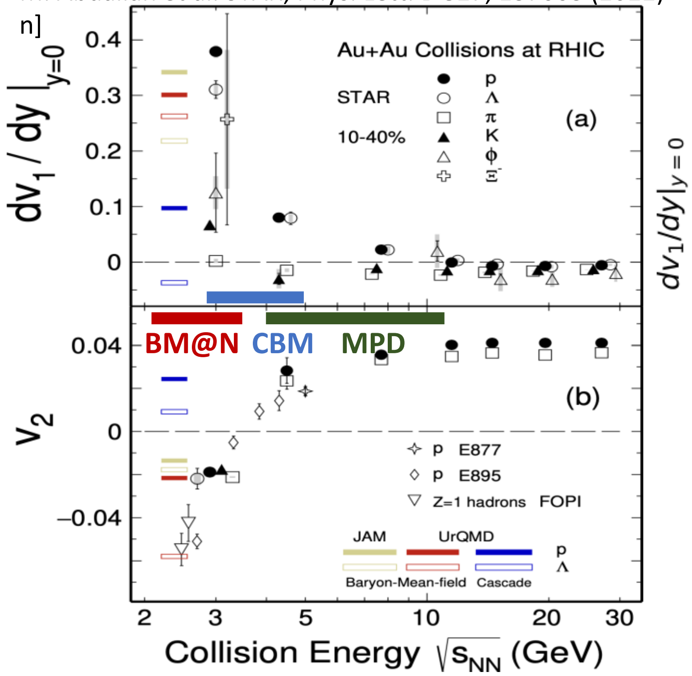


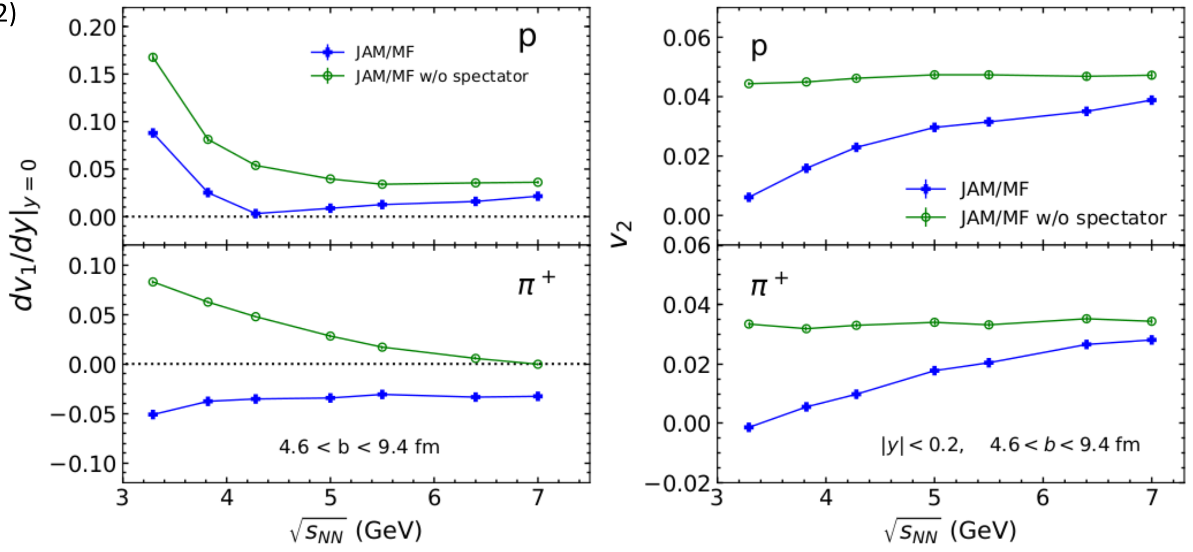
Jetscape PRL.126.242301
Trjactum PRL.126.202301

Major uncertainty: initial condition and pre-hydro phase

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)

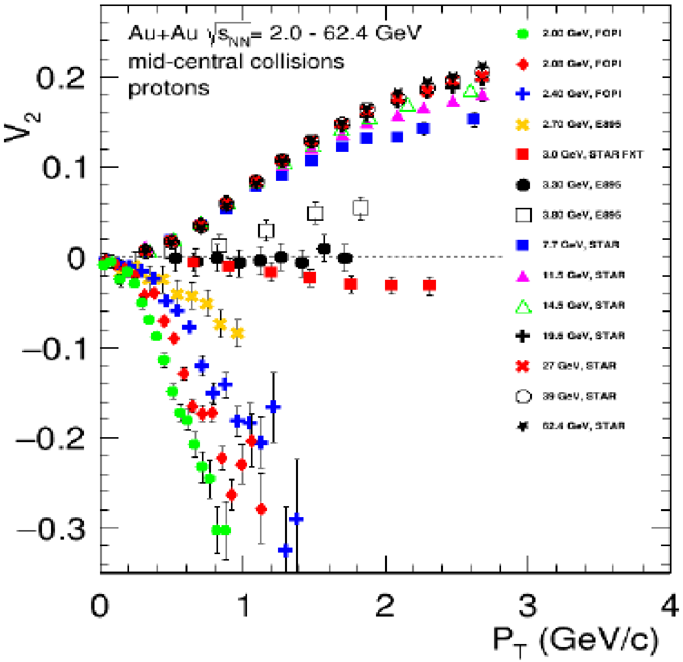
Anisotropic flow at FAIR/NICA energies is a delicate balance between:

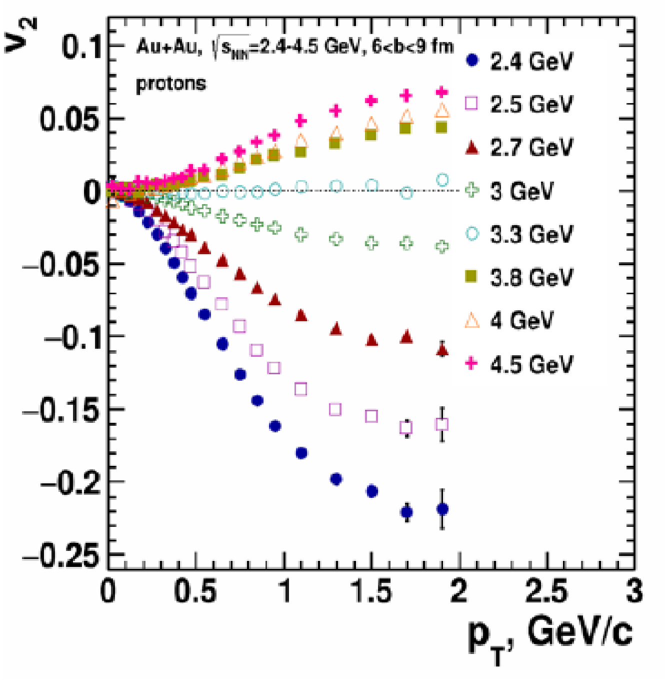
I. The ability of pressure developed early in the reaction zone ($t_{exp} = R/c_s\,, c_s = c\sqrt{dp/d\varepsilon}$) and

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

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

Particles 6 (2023) 2, 622-637





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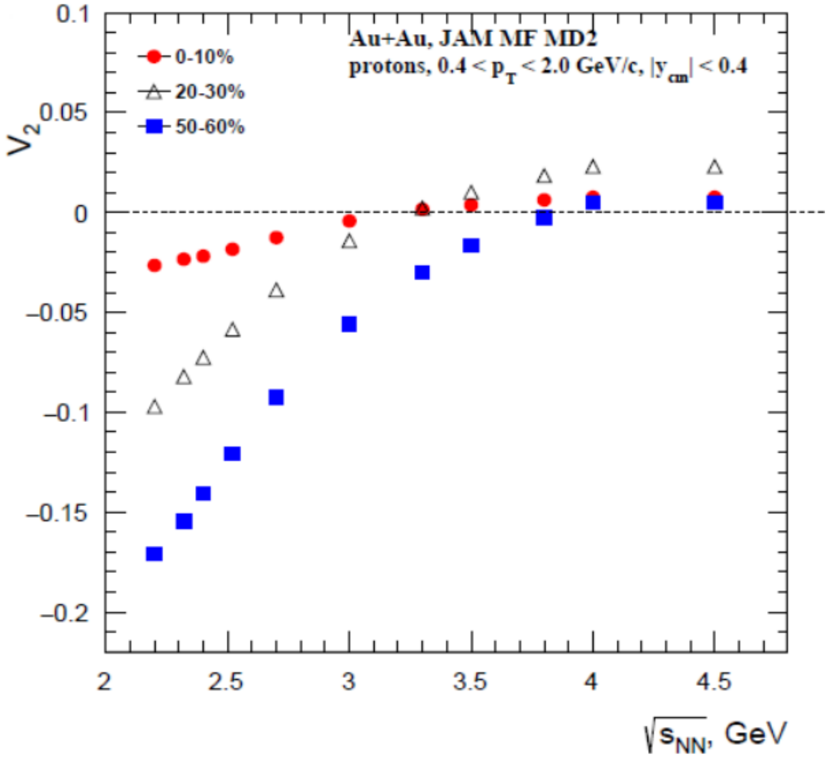
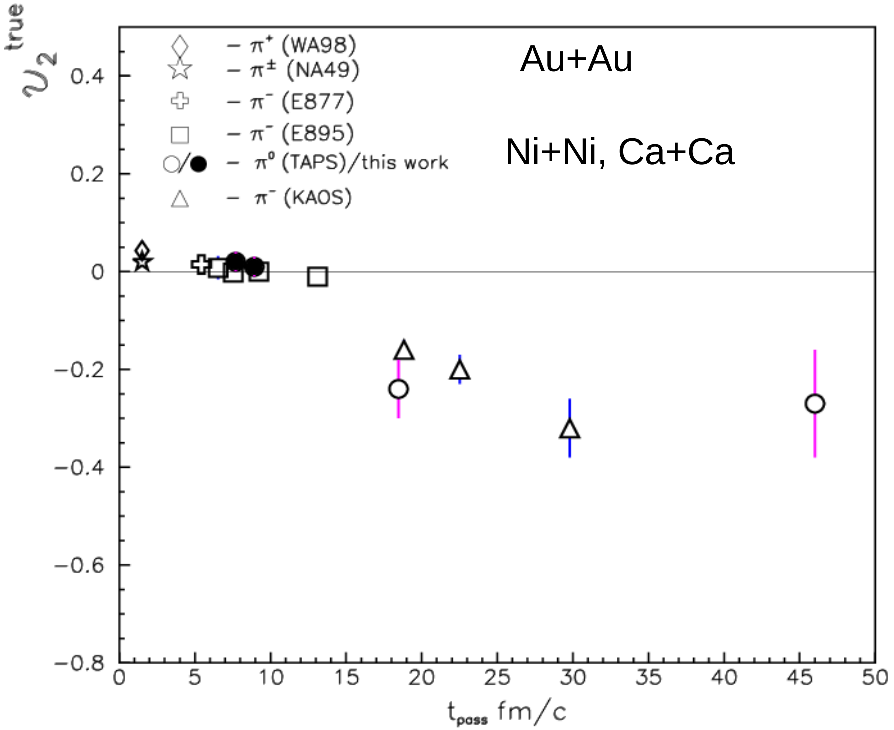
Elliptic flow: transition from out-of-plane to in-plane: geometry

P. Parfenov, Particles 5 (2022) 4, 561-579

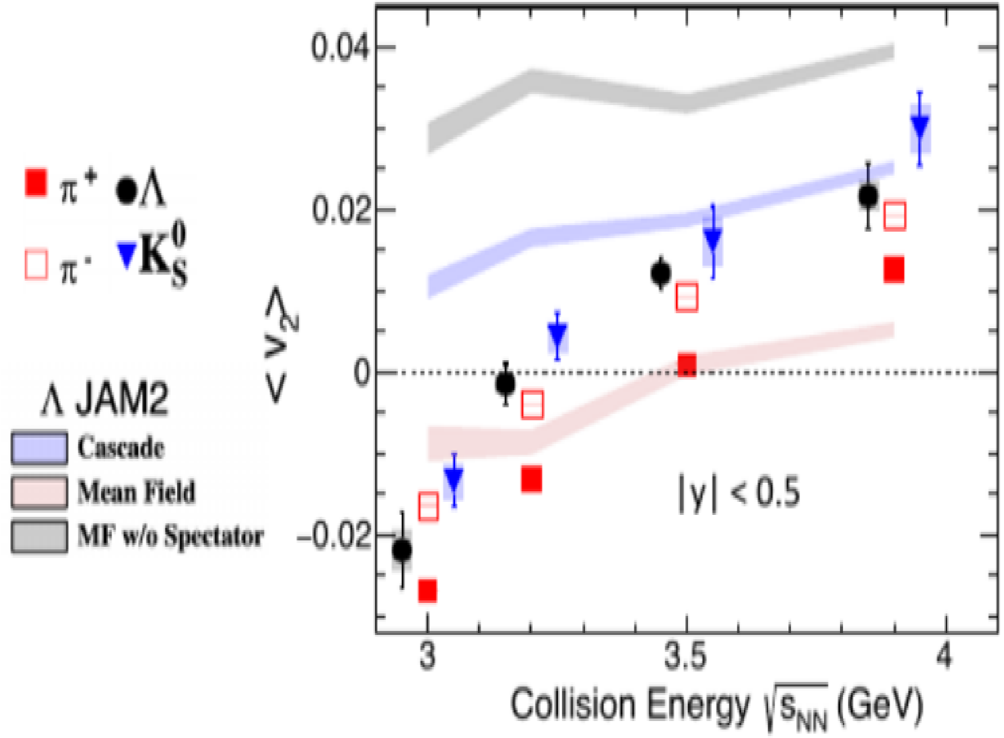


A.T Czech.J.Phys. 50S4 (2000) 139-166

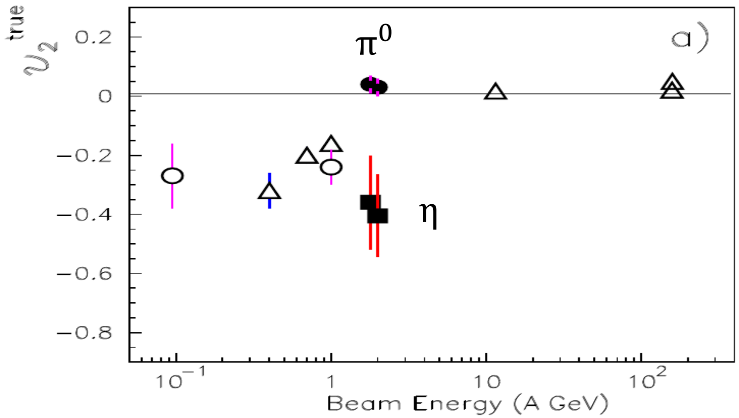


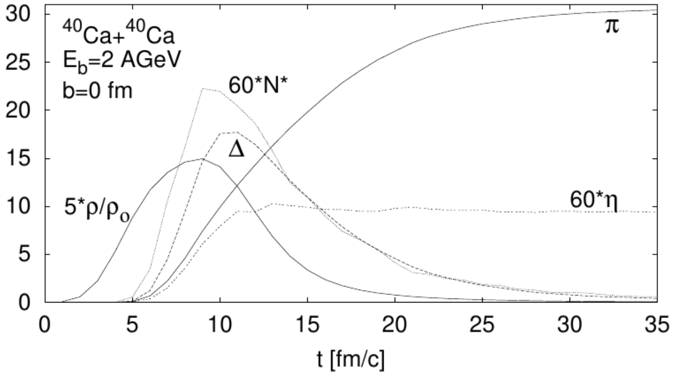
Elliptic flow: transition from out-of-plane to in-plane: PID

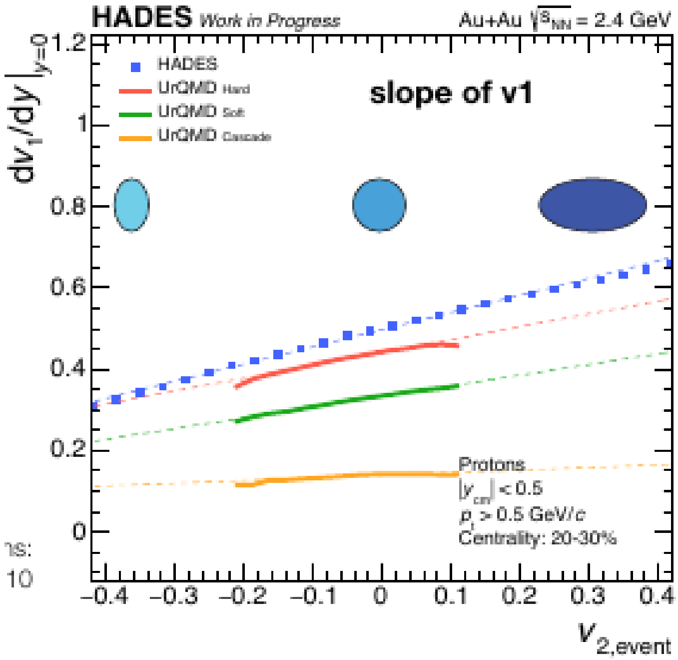
Li-Ke Liu (CCNU), STAR Collaboration, CPOD 2024



A.T Czech.J.Phys. 50S4 (2000) 139-166







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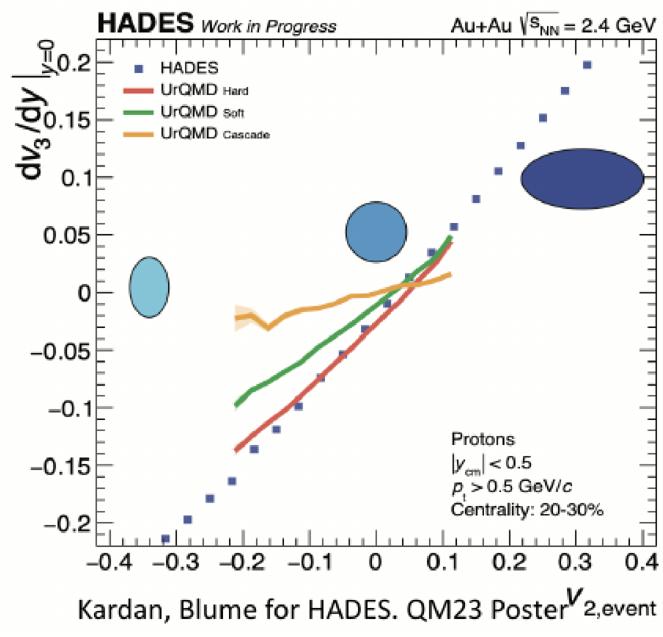
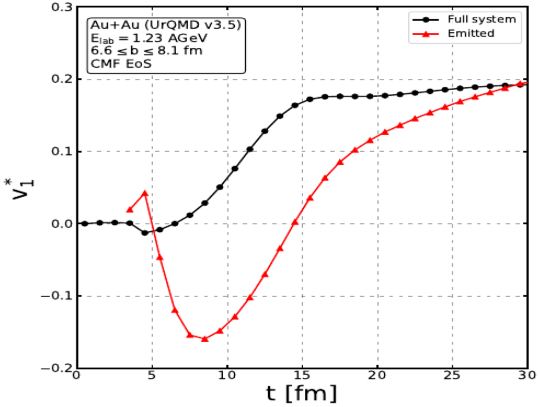


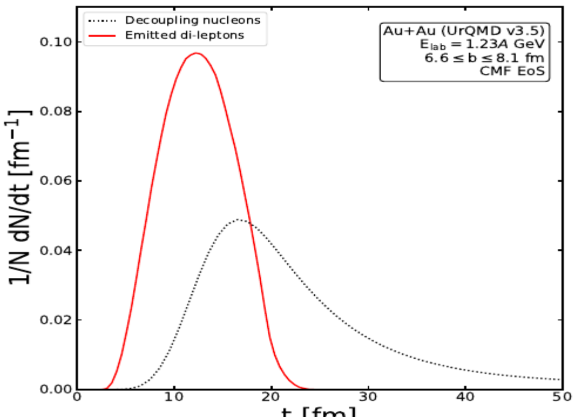
Kardan, Blume for HADES. QM23 Poster

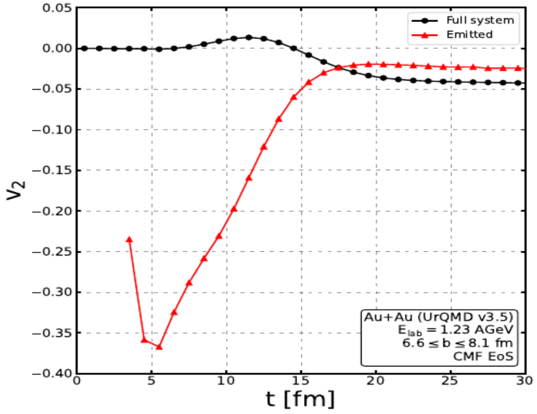
New HADES results on flow correlations

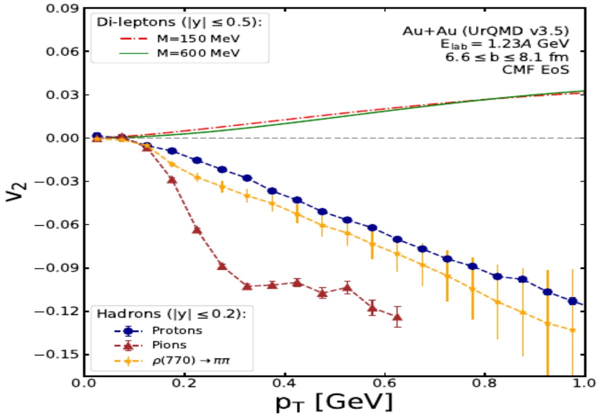
Decoding the flow evolution using hadron V_1- V_2 correlations and dileptons

Tom Reichert et al., Phys.Lett.B 841 (2023) 137947







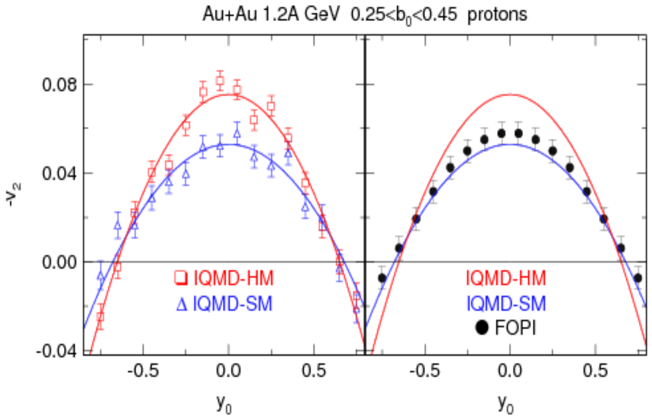


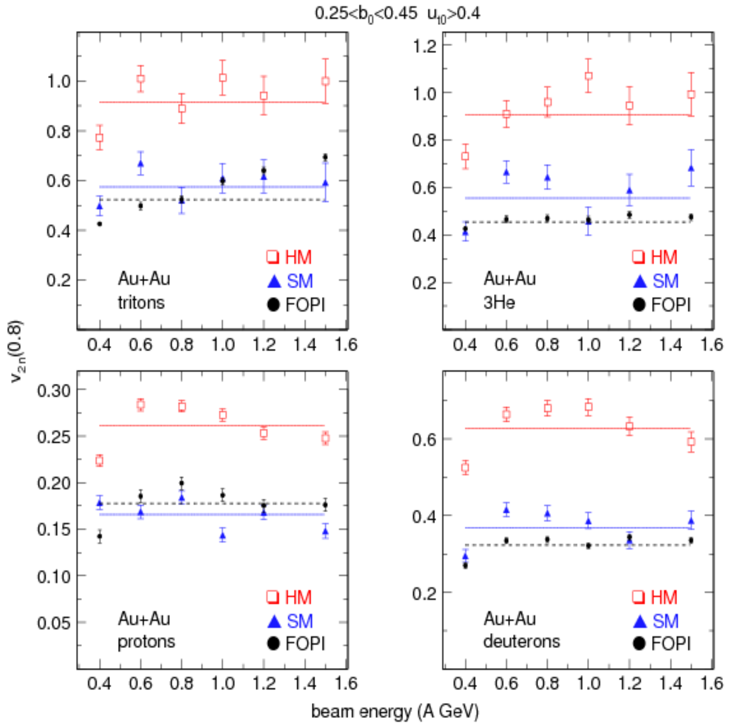
Use dileptons as independent probe to observe the early expansion of the matter

Rapidity dependence of v2 and EOS

FOPI data : Nucl. Phys. A 876 (2012) 1
IQMD : Nucl Phys. A 945 (2016)

HM – stiff momentum dependent with K=376 MeV
SM – soft momentum dependent with K=200 MeV

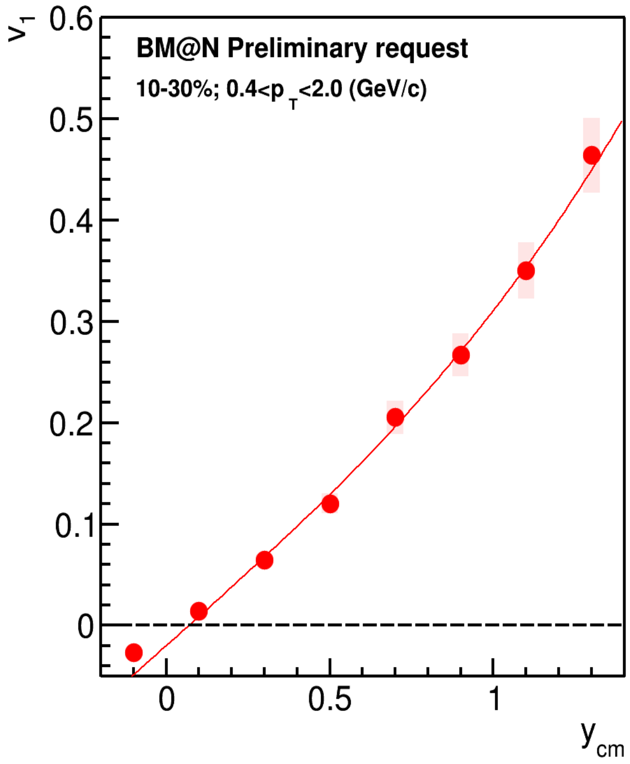


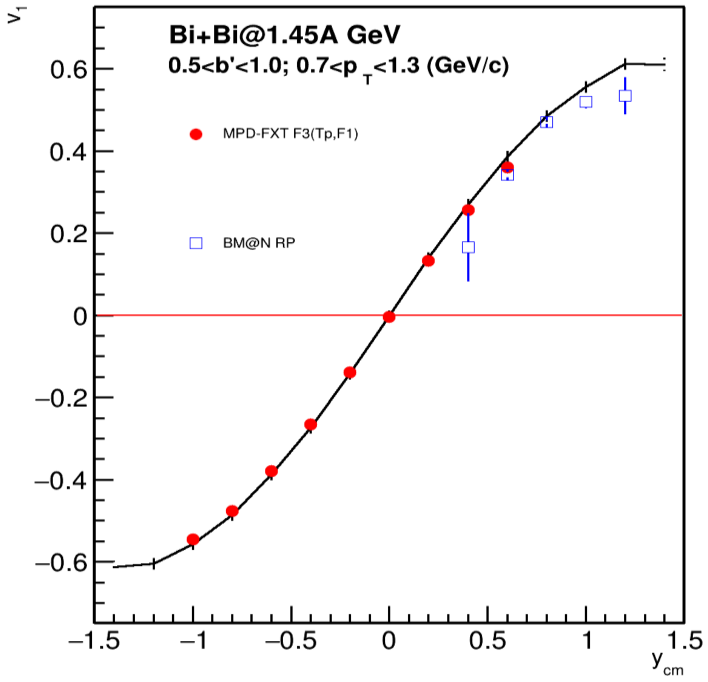


V2n=|V20|+|V22|
Fit: V2(y0)=V20+V22*Y0^2

Large rapidity coverage is important for flow measurements: MPD forward upgrade

Directed flow of protons: BM@N – MD FXT

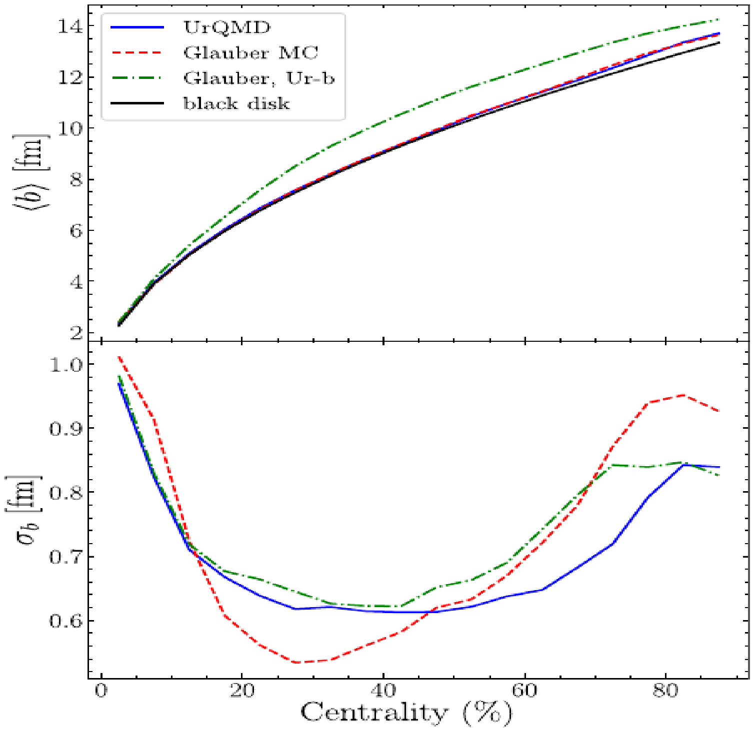


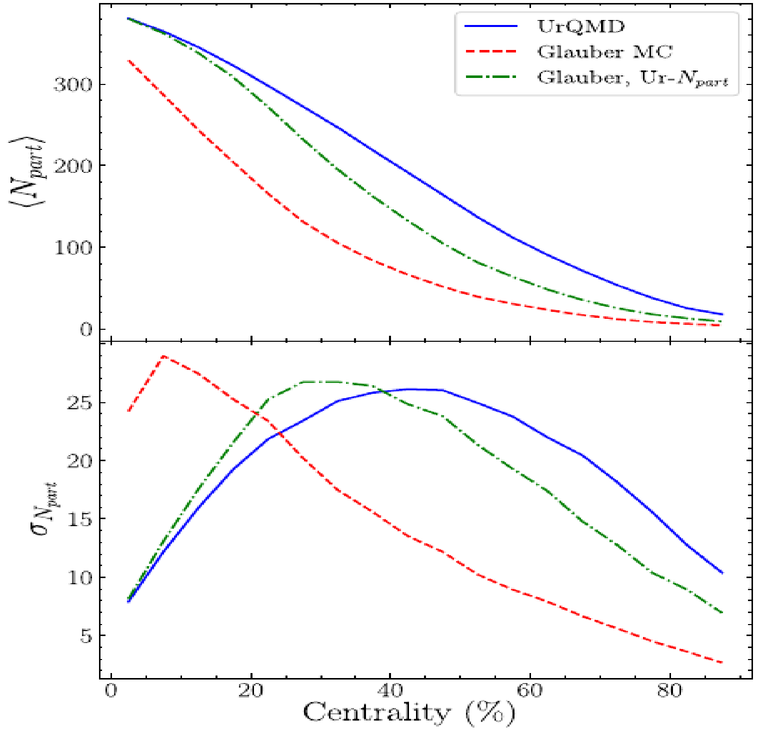


Please see Mikhail Mamaev and Peter Parfenov talks at the workshop

Collision centrality issue

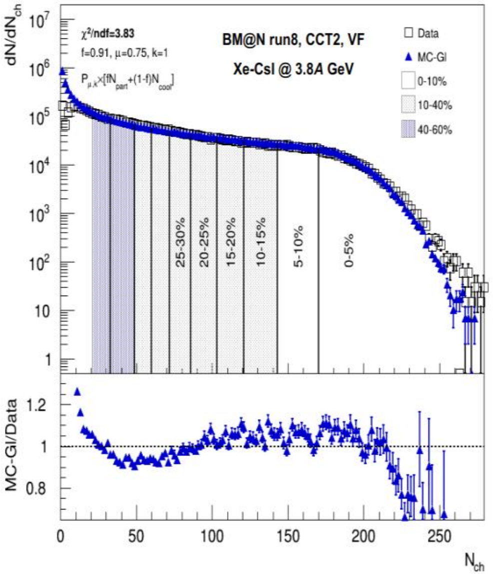
M. O Kuttan et al., Eur. Phys. J. C (2023) 83:792

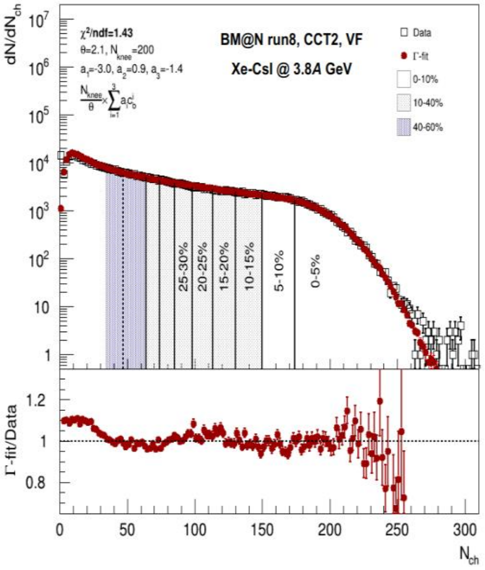


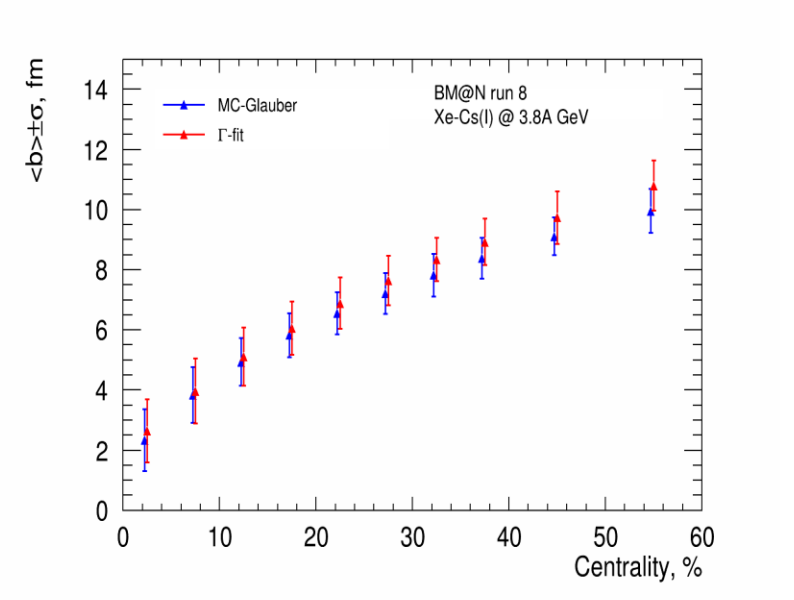


N_{part} is a strongly model dependent quantity. In addition, for any given centrality class, Glauber MC and UrQMD predicts drastically different N_{part} distributions.
The impact parameter b and the number of charged particles N_{ch} are much more correlated and give an almost model independent centrality estimator.

Collision centrality: different estimators







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Finite-Size Effects and search for CEP

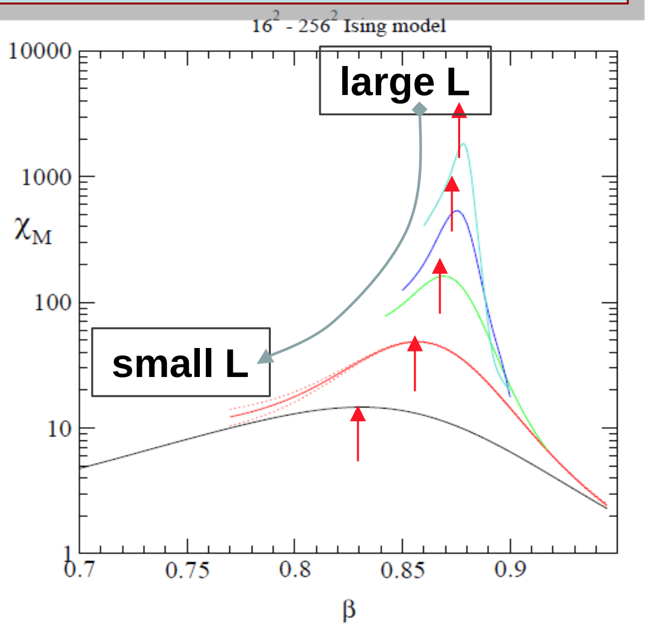
In HIC, both the size (**L**) and duration of formed system are finite.

Critical behavior changes with L

If the L is too small, the correlation length **ξ** can not be fully developed to cause a phase transition.

$$\xi \sim |T - T_c|^{-\nu} \leq L$$

if the correlation length the finite-size effect is not negligible and only a **pseudo-critical point, shifted from the genuine CEP, is observed.**



Note change in peak heights positions & widths with L

- ✓ **Finite-size effects have a specific dependencies on size (L)**
- ✓ **The scaling of these dependencies give access to the CEP's location, it's critical exponents and scaling function.**

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 energies 2.5-11 GeV (SIS, STAR BESII, NICA, FAIR) shows strong energy dependence: possible** transition between hadronic and partonic matter.
- **System size scan is very important in order to understand the effect of spectators on the experimental observables**

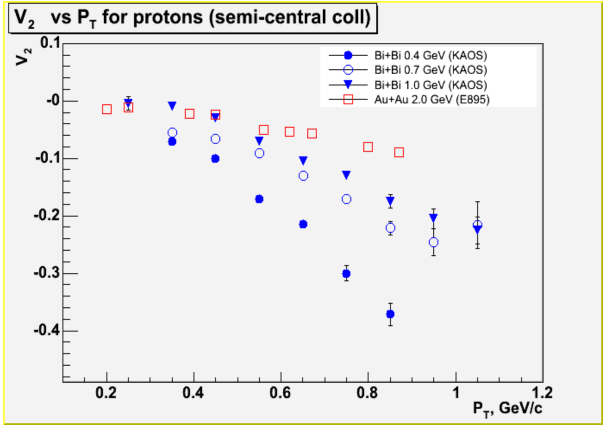
- **Feasibility study for anisotropic flow in MPD/MPD FXT/ BM@N:**

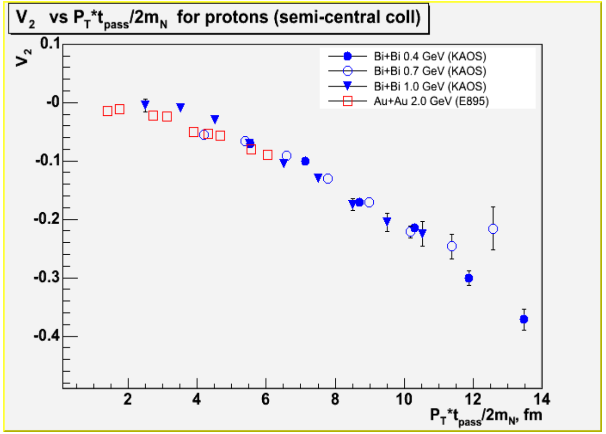
- Programs for flow analysis are available for MPD/BM@N collaborations – first preliminary flow results from BM@N will be published soon.

Backup

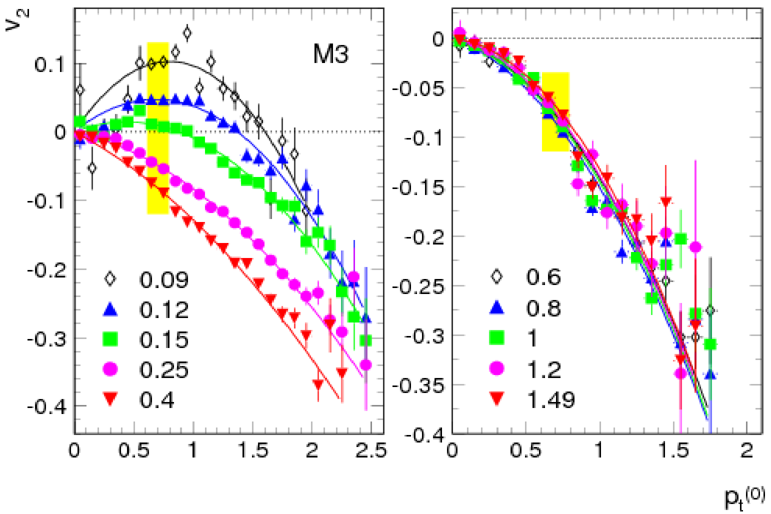
v_2 Flow at SIS-AGS: scaling relations

(KAOS – Z. Phys. A355 (1996);
(E895) - PRL 83 (1999) 1295





FOPI: v_2 of protons from
Elab=0.09 to 1.49 GeV
Phys.Lett. B612 (2005) 173-180



The rather good scaling observed suggest that c_s does not change significantly over beam energy range 0.4 – 2.0 AGeV.

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

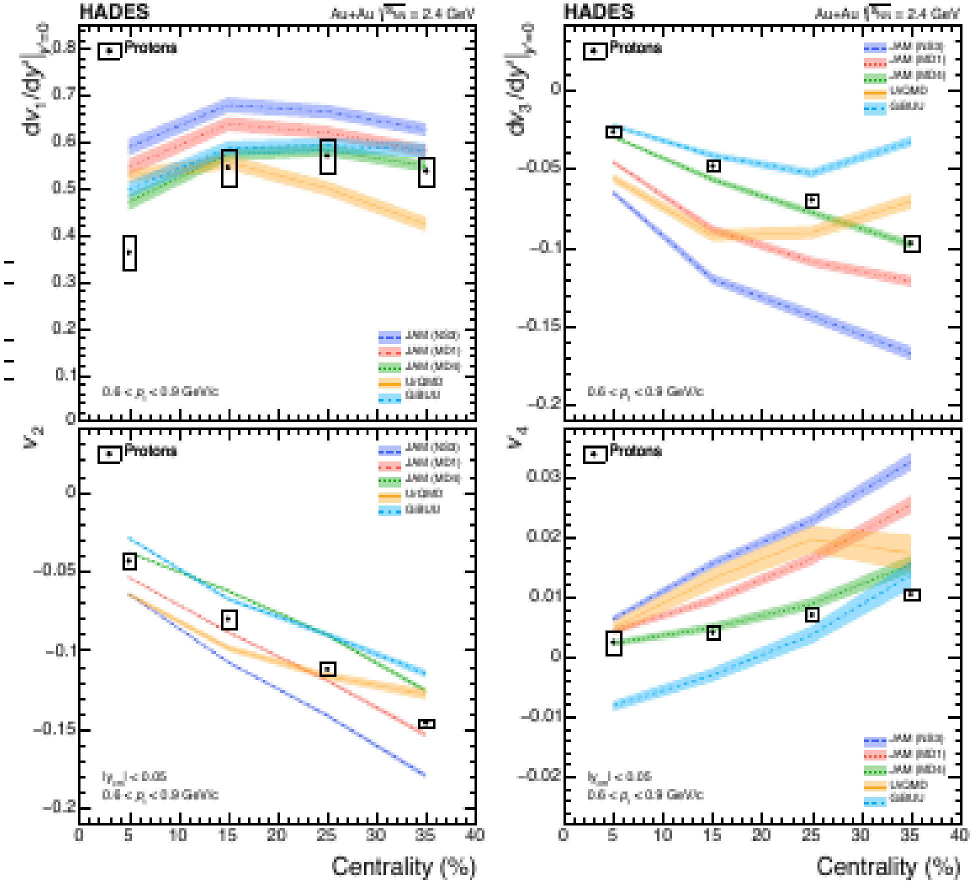
Models:

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 1.9059	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

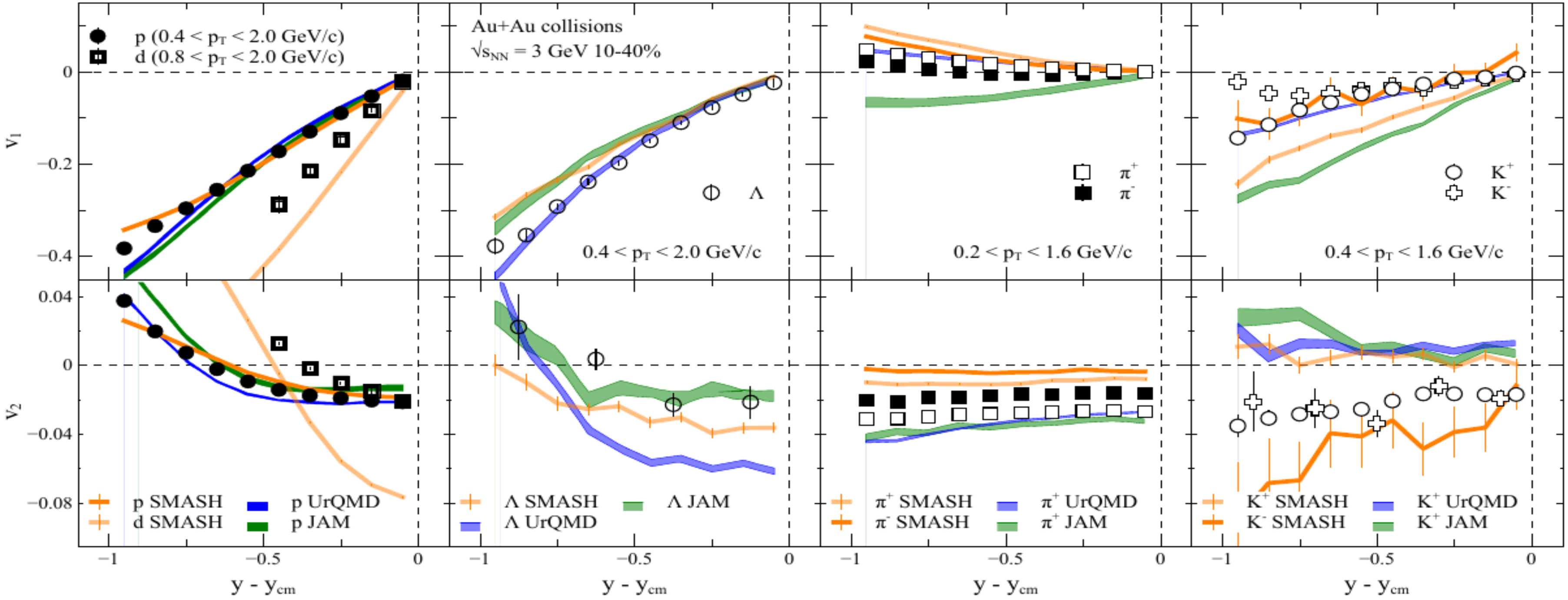
Conclusions

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