Energy/System Size/Rapidity Scan - Flow

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MEPhI
National Research
Nuclear University

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Experiments: BM@N and MPD at NICA

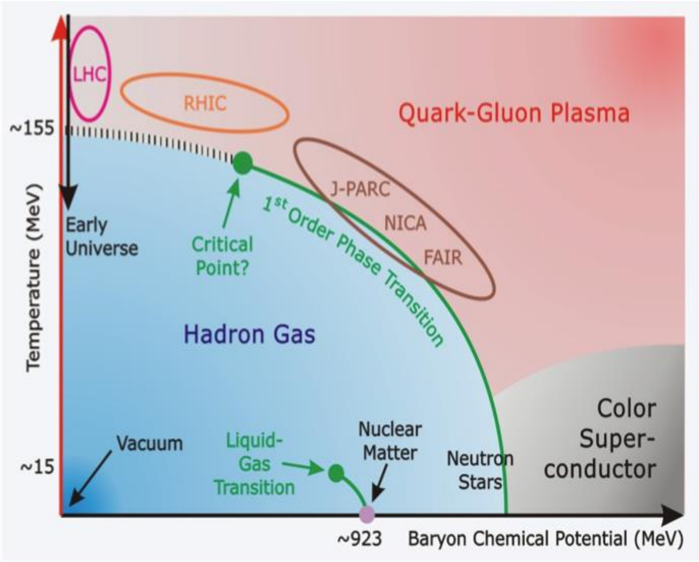
HADRON

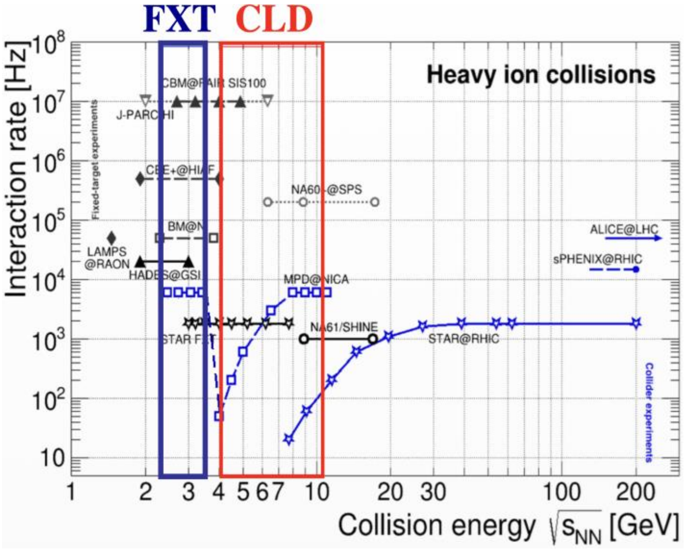
QGP

Bevalac ~1 GeV → **AGS** ~5 GeV → **SPS** ~20 GeV → **RHIC** ~100 GeV → **LHC** ~5000 GeV

FAIR; NICA ← **RHIC/BES** ←

QGP may be produced at low energies; QGP is produced in high energy collisions

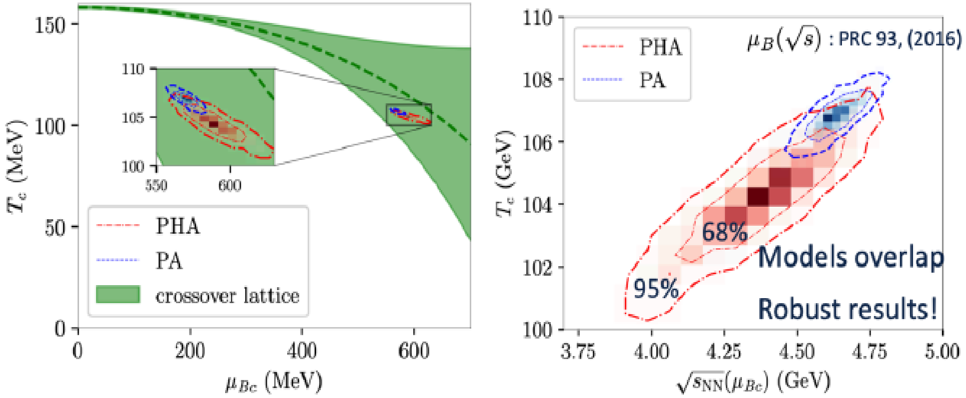




Experiments BM@N ($\sqrt{s_{NN}}$= 2.3−3.3 ГэВ) and MPD ($\sqrt{s_{NN}}$= 4−11 ГэВ)

Ion sources: C (A=12), N (A=14), Ar (A=40), Fe (A=56), Kr (A=78-86), Xe (A=124-134), Bi (A=209).

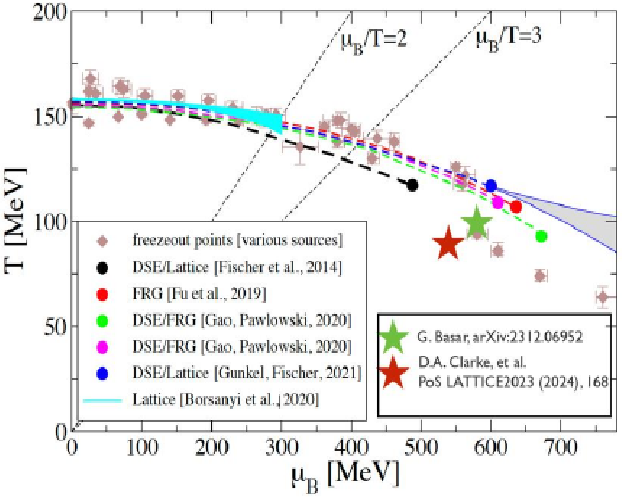
Location of the QCD Critical Point : Theoretical Estimation/Prediction



Models overlap

Robust results!

Holography+ Bayesian : Hippert et al., arXiv : 2309.00579



G. Basar, arXiv:2312.06952

D.A. Clarke, et al. PoS LATTICE2023 (2024), 168

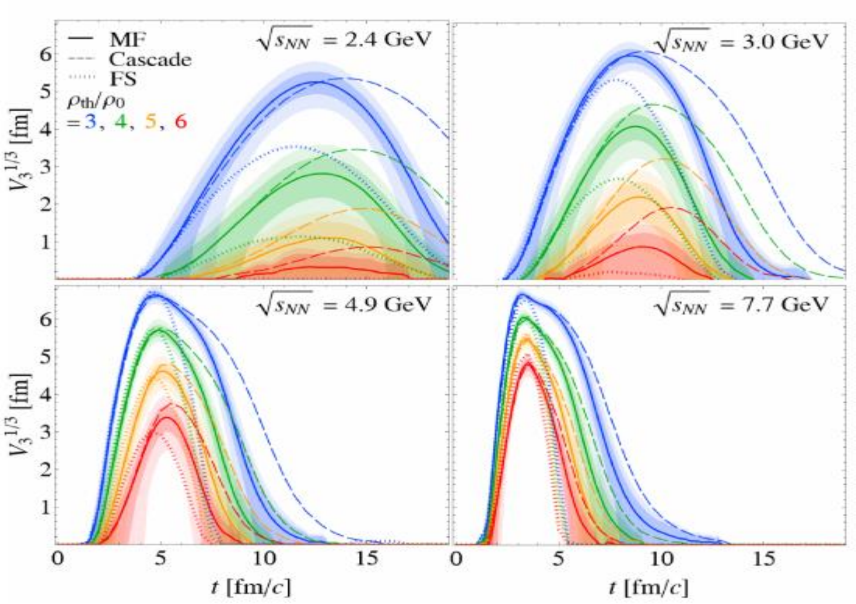
CPOD2024

Method	μ_c (MeV)	T_c (MeV)
Holography + Bayesian	560 - 625	101 - 108
FRG/DSE	495 - 654	108 - 119
Lee-Yang edge singularities	500 - 600	100 - 105
Lattice QCD	$\mu_c/T_c > 3$	F. Karsch et al.
Summary	**495 - 654**	**100 - 119**

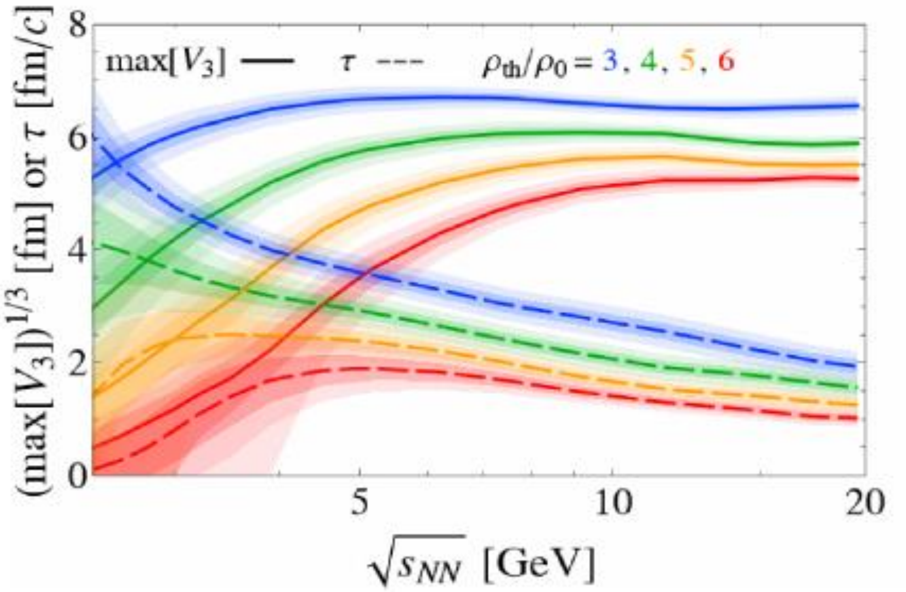
(μ_c, T_c) = (495 - 654, 100 - 119) MeV → $3.5 < \sqrt{s_{NN}} < 4.9$ GeV

Optimal collision energy for realizing high baryon-density matter

H. Taya, A. Jinno, M. Kitazawa, Y. Nara, https://arxiv.org/abs/2409.07685



Dense region disappears more quickly for larger $\sqrt{s_{NN}}$



$\sqrt{s_{NN}}$ dependence of the maximum volume max[V3] (solid) and the lifetime τ (dashed)

The optimal energy is around $\sqrt{s_{NN}}$**=3−5 GeV,** where a baryon density ρ/ρ_0 = 3 nuclear density is realized with a substantially large space-time volume. Higher and lower energies are disfavored due to short lifetime and low density

EOS for high baryon density matter

The binding energy per nucleon:

$$E_A(\rho,\delta) = \boxed{E_A(\rho,0)} + \boxed{E_{sym}(\rho)}\delta^2 + O(\delta^4)$$

Symmetric matter

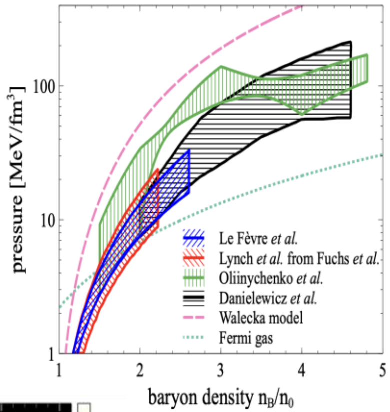
Symmetry energy

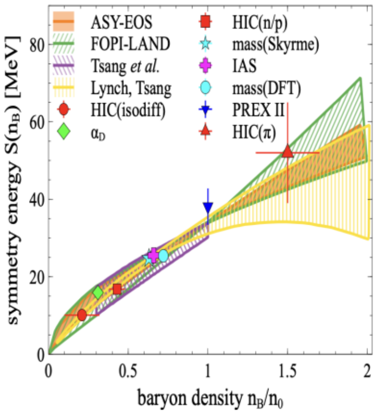
Isospin asymmetry:

$$\delta = (\rho_n - \rho_p)/\rho$$

Heavy-Ion Collisions and Merging Neutron Stars

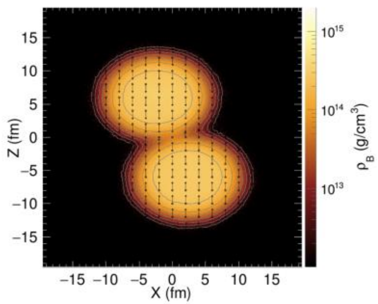
- ☐ T<70 MeV, $\rho \cong 3\rho_0$ for both
- ☐ Probe NS merger matter in the laboratory



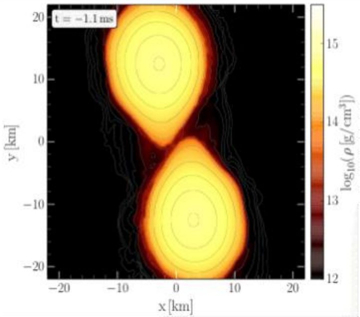


A. Sorensen et. al., Prog.Part.Nucl.Phys. 134 (2024) 104080

Au+Au 1.25A GeV



NS mergers



New data is needed to further constrain transport models with hadronic d.o.f.

Anisotropic flow in heavy-ion collisions at high baryon density

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

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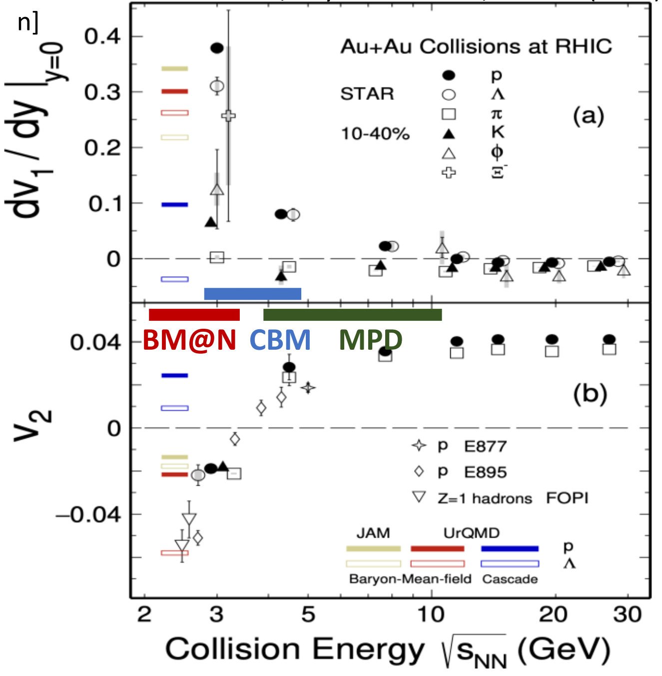
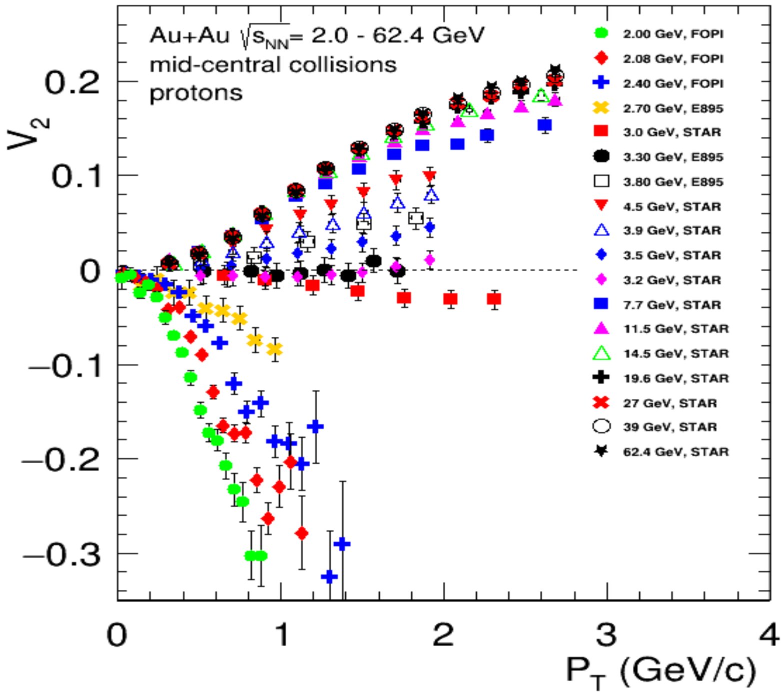
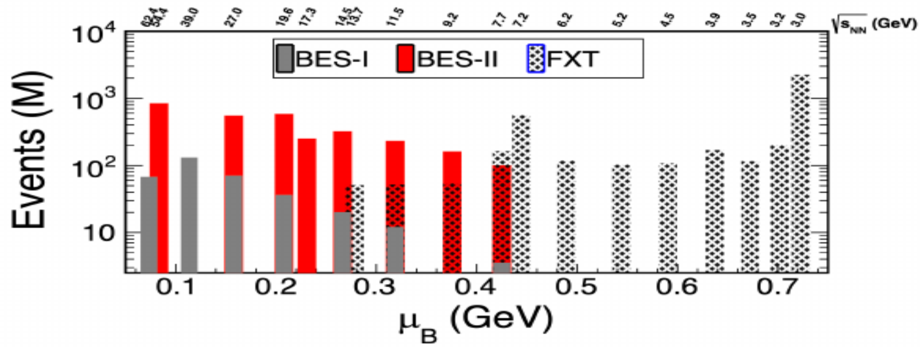




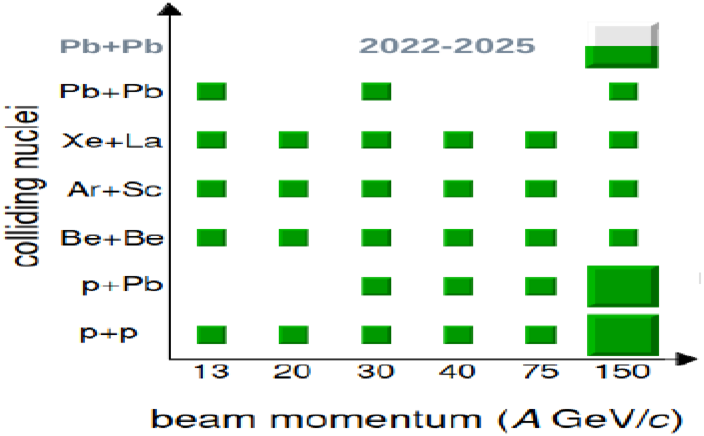
Anisotropic flow at NICA energies : strong energy dependence

Beam Energy / System size Scan programs

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

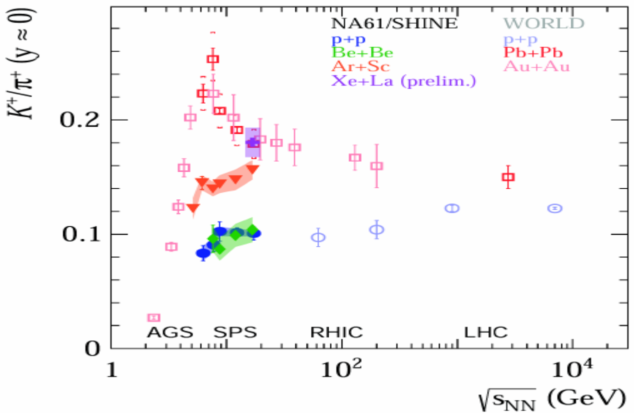


NA61SINE at SPS: 5.1 < $\sqrt{s_{NN}}$ < 17 (27) GeV

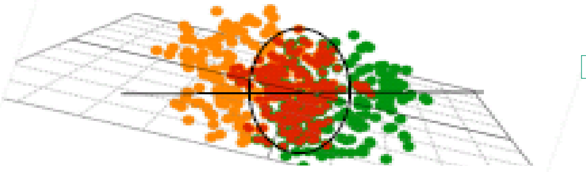


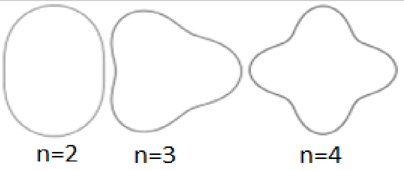
Au+Au Collisions at RHIC

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



Anisotropic Flow at RHIC-LHC



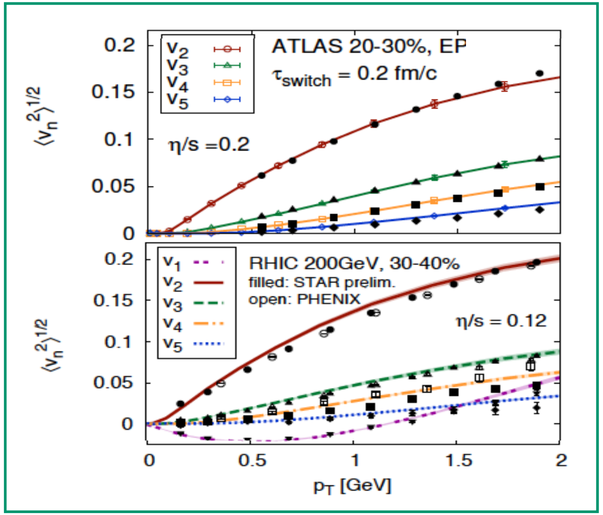


$$\epsilon_n = \sqrt{\frac{\langle r^n \cos n\phi\rangle + \langle r^n \sin n\phi\rangle}{\langle r^n\rangle}}$$

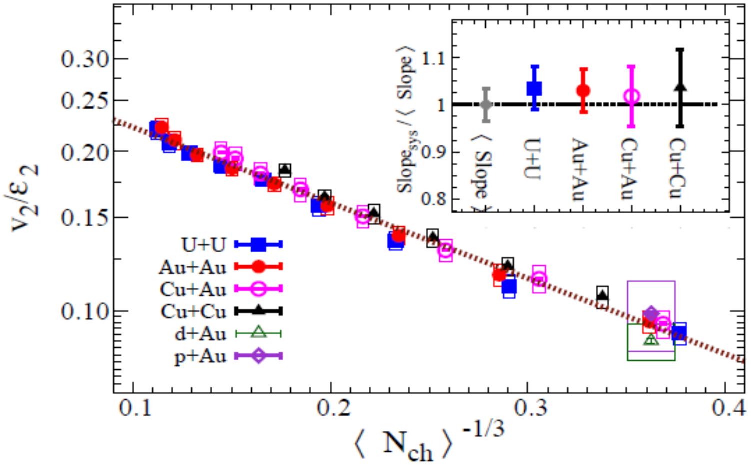
$$\frac{dN}{d\phi} \propto \left(1 + 2\sum_{n=1} v_n \cos\left[n\left(\phi - \Psi_n\right)\right]\right)$$

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



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,**

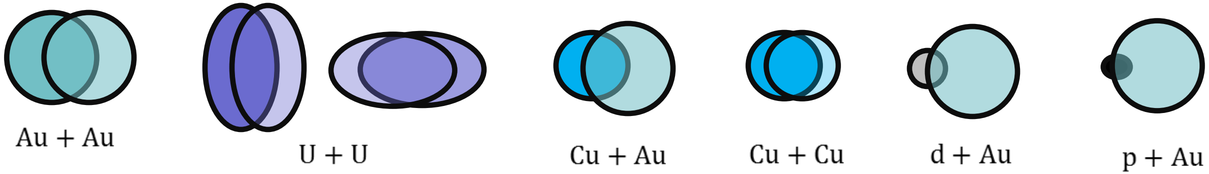
$$\frac{\mathbf{v_n}}{\boldsymbol{\varepsilon}_\mathbf{n}} \propto \mathbf{e}^{-\boldsymbol{\beta}\,\mathbf{n}^2}, \quad \boldsymbol{\beta} \propto \frac{\boldsymbol{\eta}}{\mathbf{s}} \frac{\mathbf{1}}{\mathbf{R\,T}}$$

arXiv:1601.06001
Roy A. Lacey, et al.

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

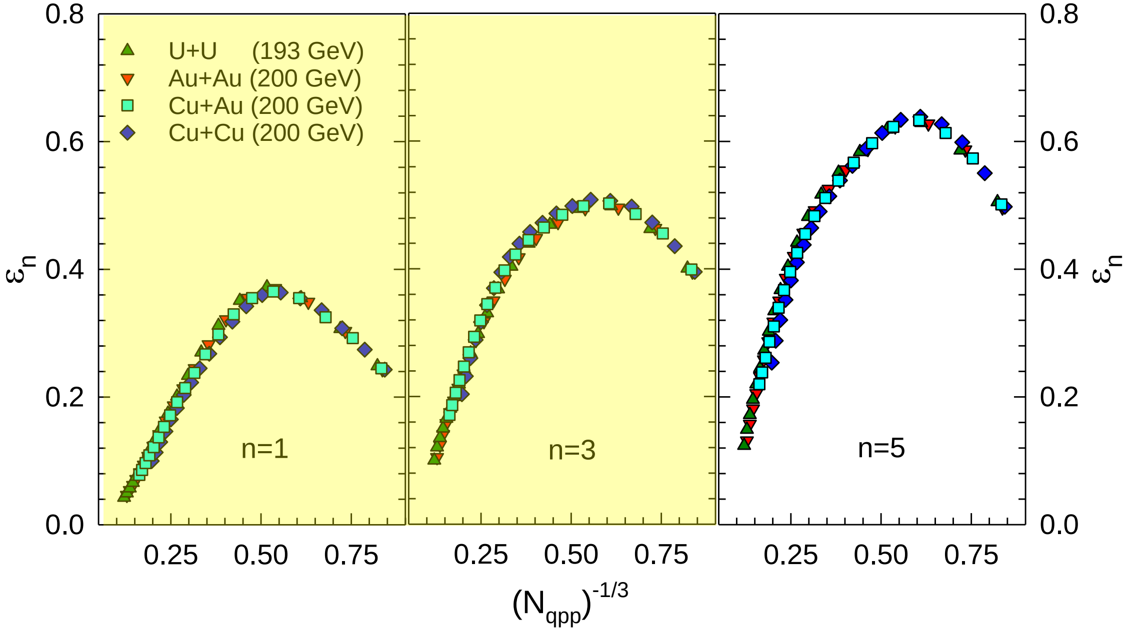
PRC 88, 044915 (2013)
E. Shuryak and I. Zahed

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



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

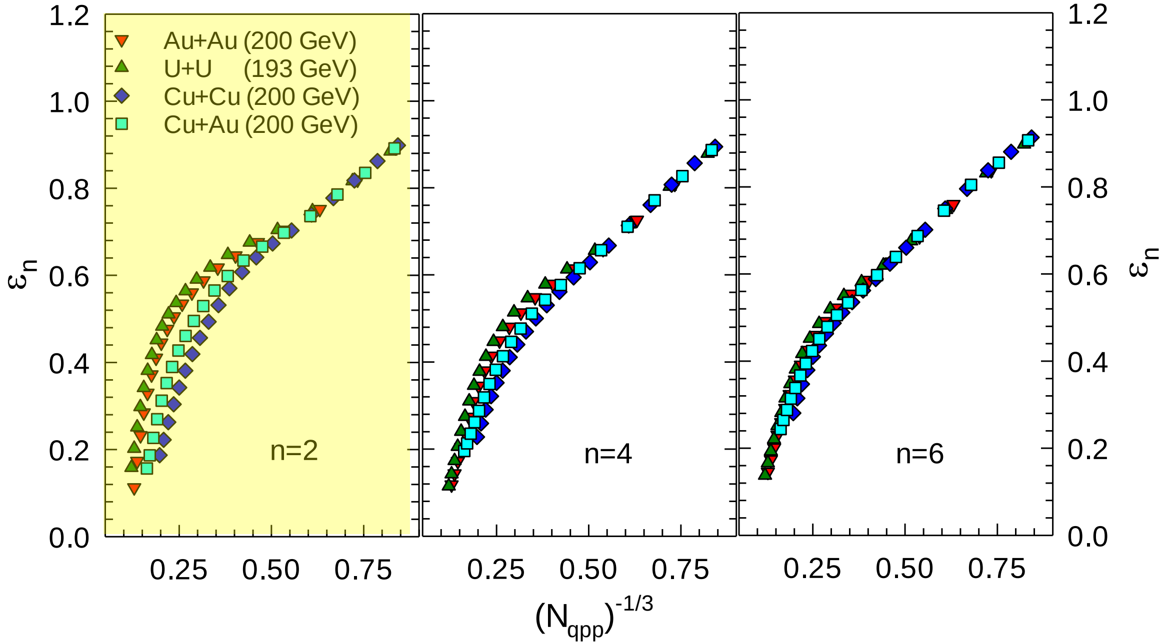
Acoustic Flow – Expected Shape Response



- ➢ Odd eccentricity moments are fluctuations driven
  - ✓ Little, if any, system dependence for A+A(B) collisions for similar geometric size

courtesy of R.A. Lacey

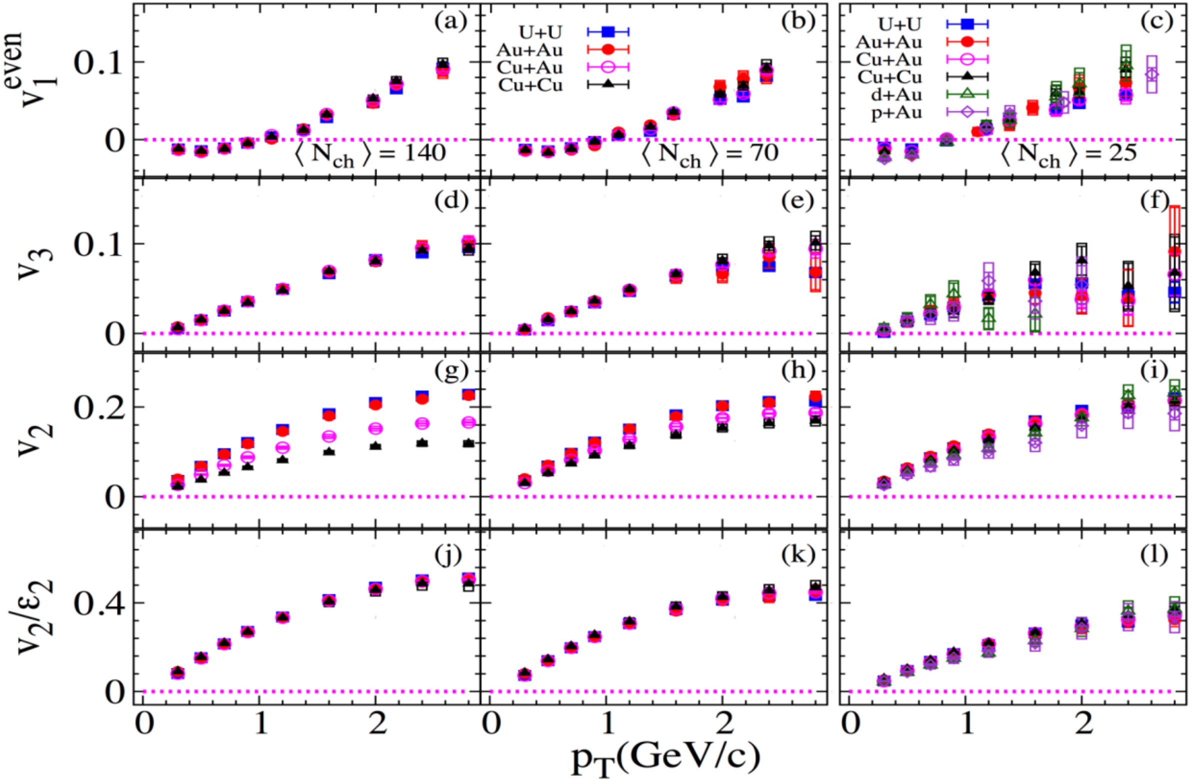
Acoustic Flow – Expected Shape Response



- **Even eccentricity moments are shape driven**
  - ✓ **Sizeable system dependence for A+A(B) collisions in central & mid-central collisions**
  - ✓ **System independence in peripheral collisions**

courtesy of R.A. Lacey

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



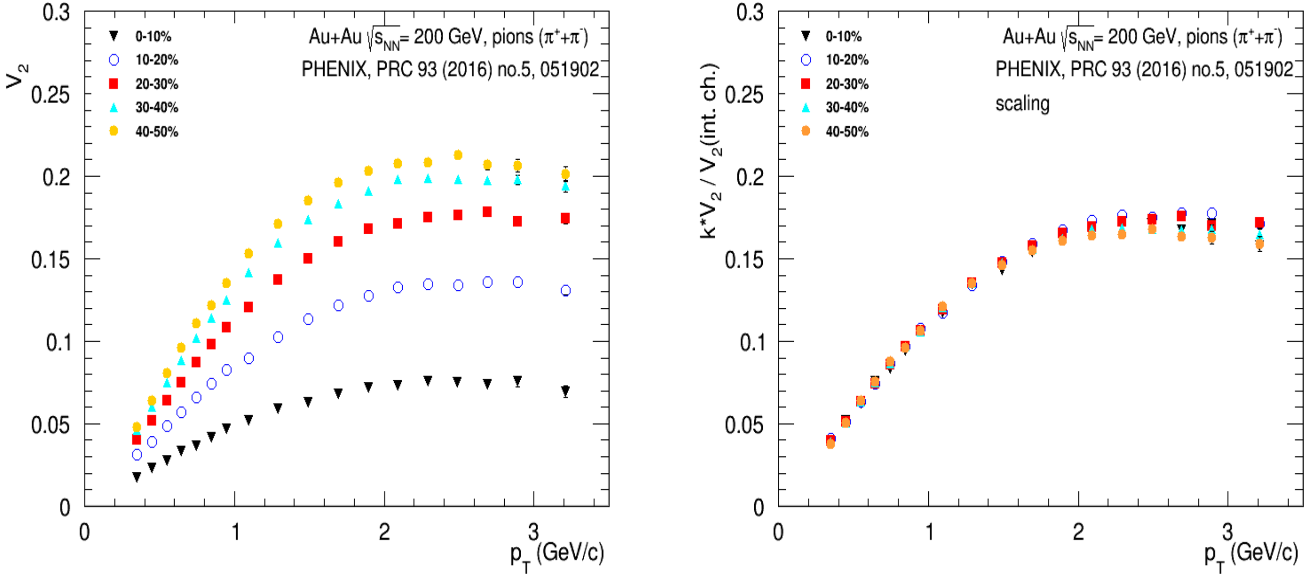
For a fixed <Nch>, the v_2/ε_2 are similar for different systems

Even harmonics are system dependent.1

Odd harmonics are system independent.

V_2 of identified hadrons at top RHIC energy: pions

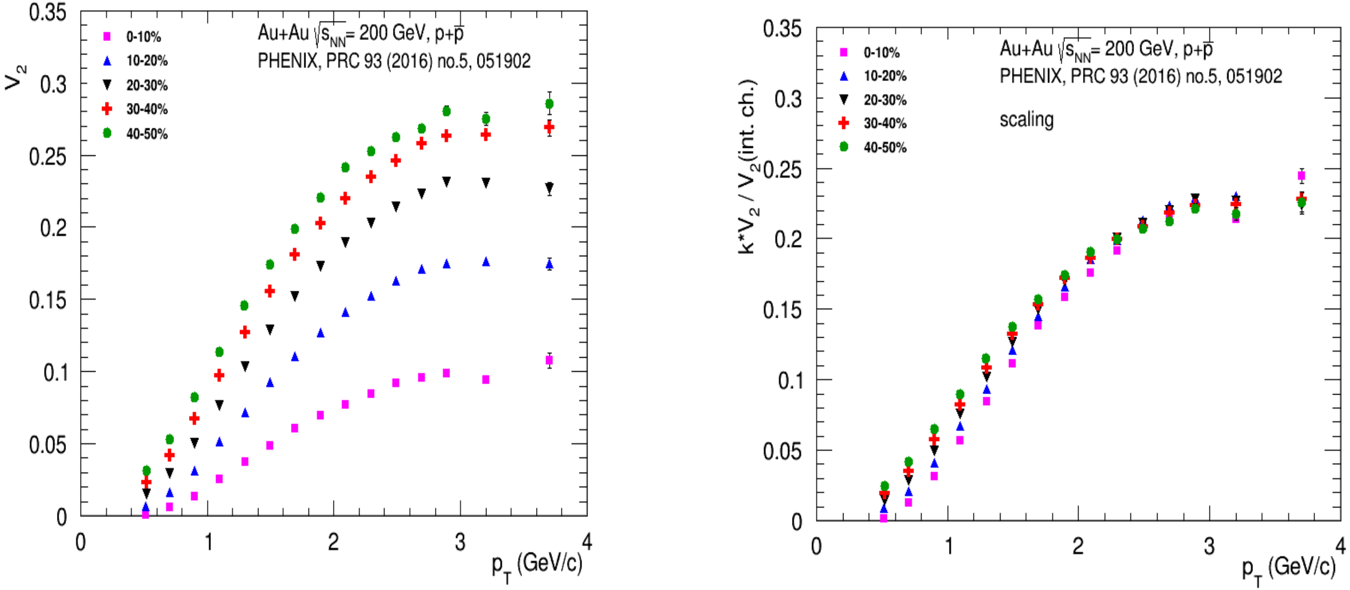
Scaling with integral flow of charged hadrons



$$V_2(PID, p_T, centrality, \sqrt{S_{NN}}) = V_2(h, centrality, \sqrt{S_{NN}})^* \, V_2(PID, p_T)???$$

V_2 of identified hadrons at top RHIC energy: protons

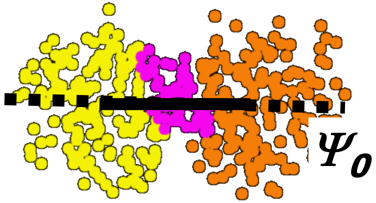
Scaling with integral flow of charged hadrons

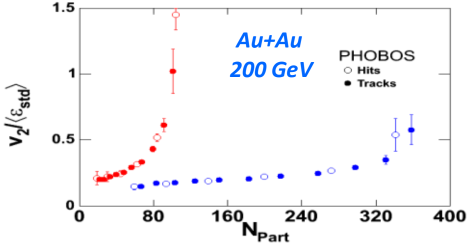


for protons the strong radial flow "blueshifts" the entire flow signal to higher p_T : $p_T \sim p_T^{th} + mc\beta$

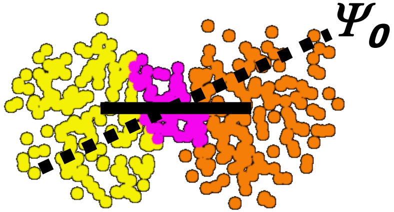
System size scan at top RHIC energy

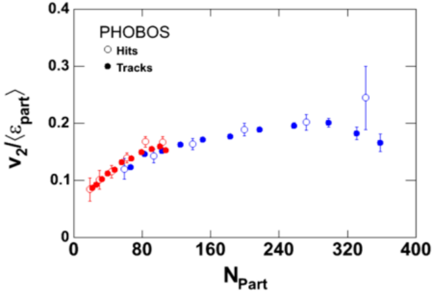
2001-2005 $\varepsilon_{\text{std}} = \frac{\sigma_y^2 - \sigma_x^2}{\sigma_x^2 + \sigma_y^2}$



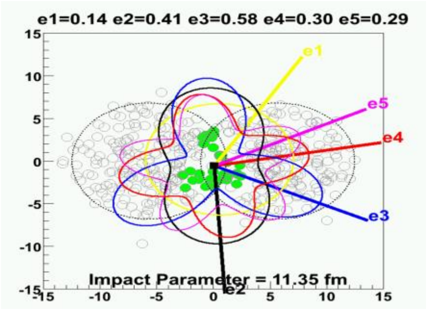


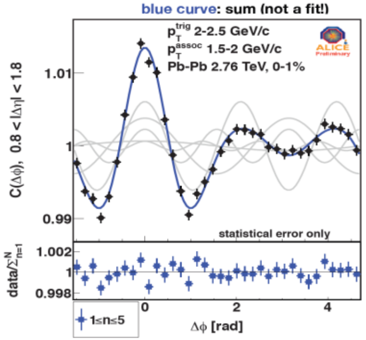
2005-2011 $\langle \epsilon_{\text{part}} \rangle = \frac{\sqrt{(\sigma_y^2 - \sigma_x^2)^2 + 4\sigma_{xy}^2}}{(\sigma_y^2 + \sigma_x^2)}$





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





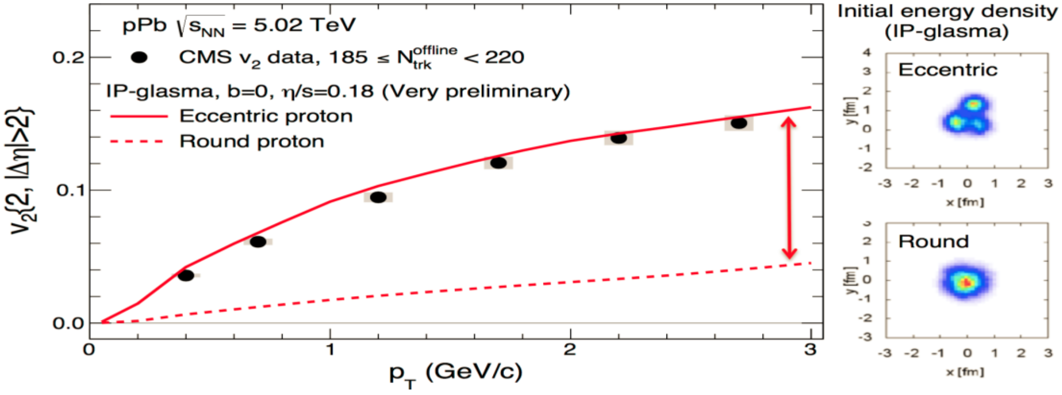
For "lumpy" *profile* $\varphi \neq \varphi + \pi$

Odd harmonics ≠ 0

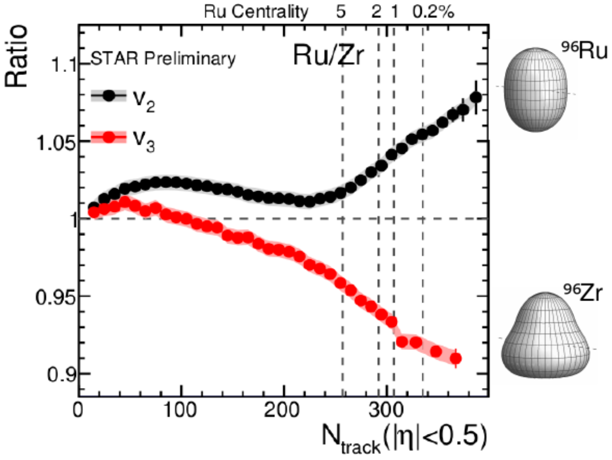
System size scan at top RHIC energy

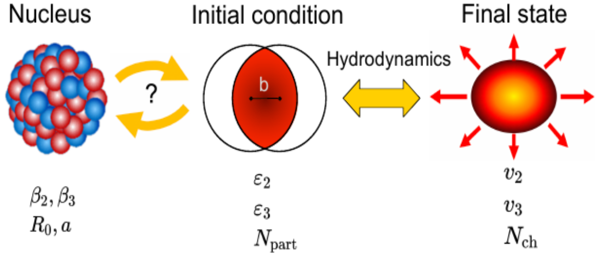
2011-2020

Nucleon substructure matters



2020-2024

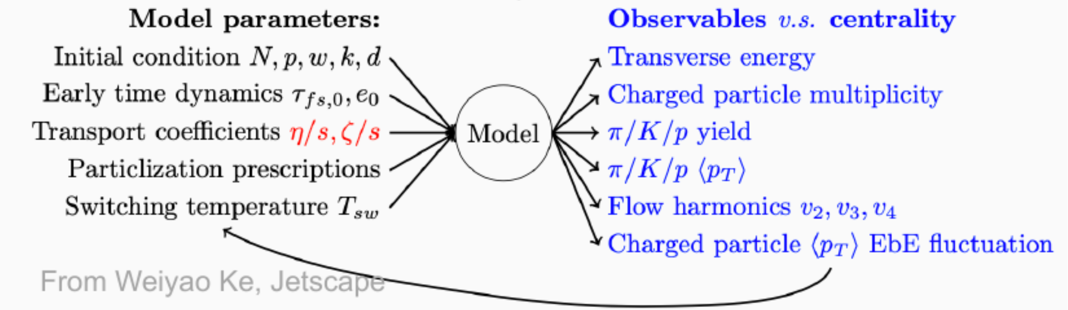




State-of-the-art modeling of HI collisions

- 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

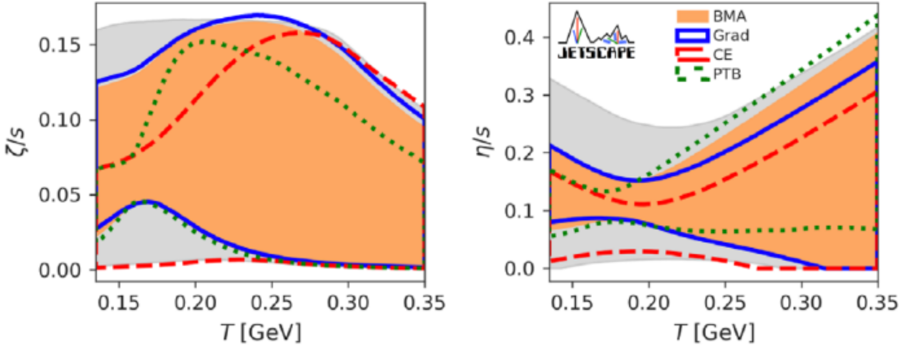
$\pi/K/p$ $\langle p_T \rangle$

Flow harmonics v_2, v_3, v_4

Charged particle $\langle p_T \rangle$ EbE fluctuation

From Weiyao Ke, Jetscape

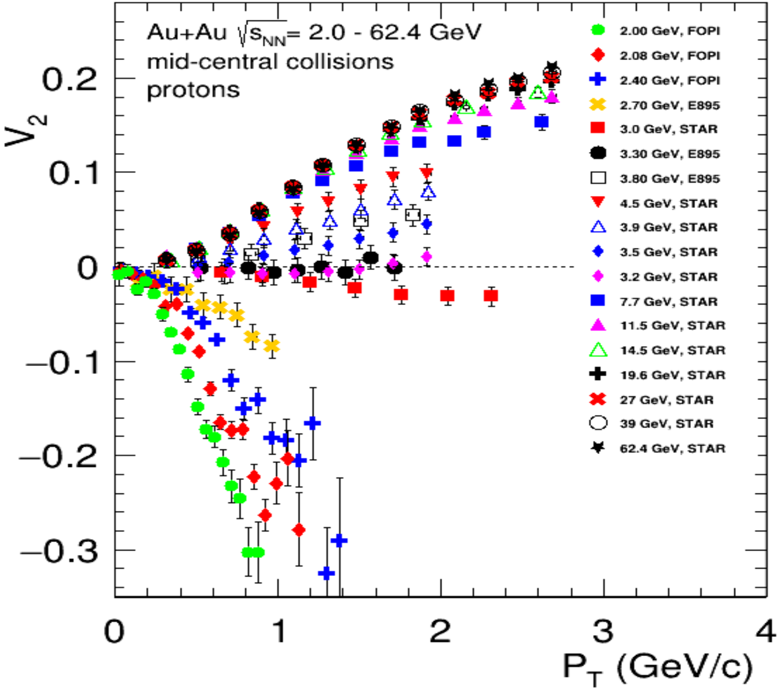
- Detailed temperature dependence of viscosity!

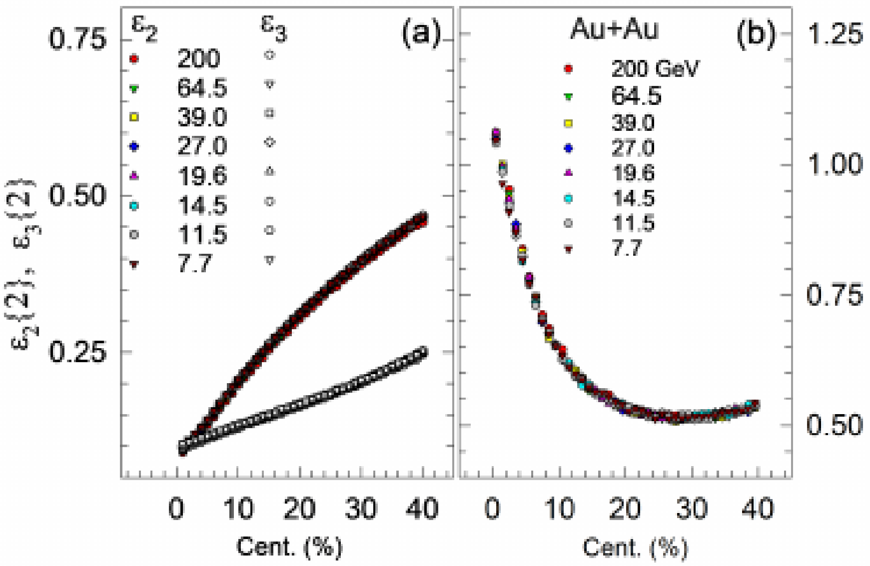


Jetscape PRL.126.242301
Trjactum PRL.126.202301

Major uncertainty: initial condition and pre-hydro phase

Anisotropic flow in Au+Au collisions: Beam Energy dependence

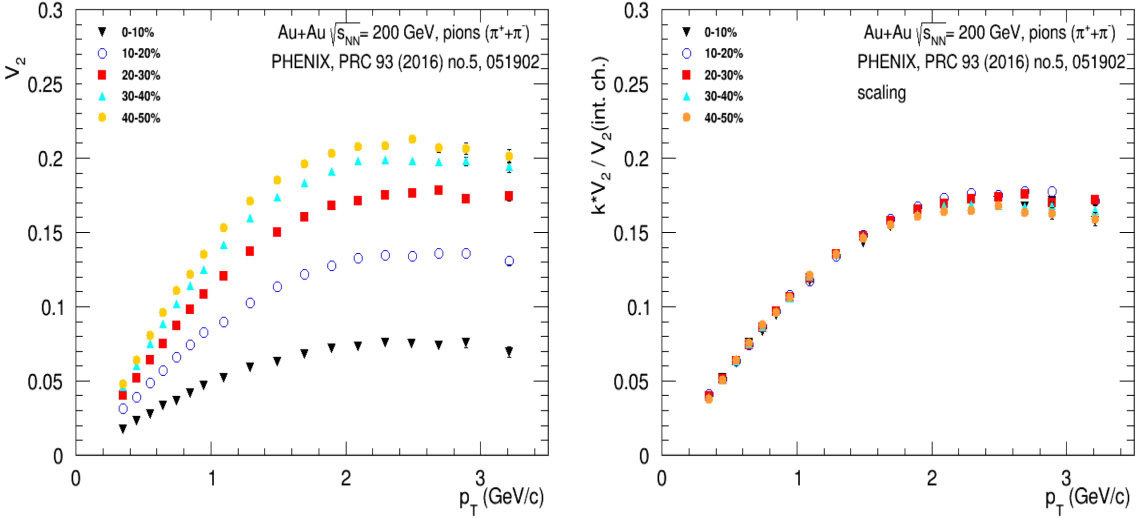


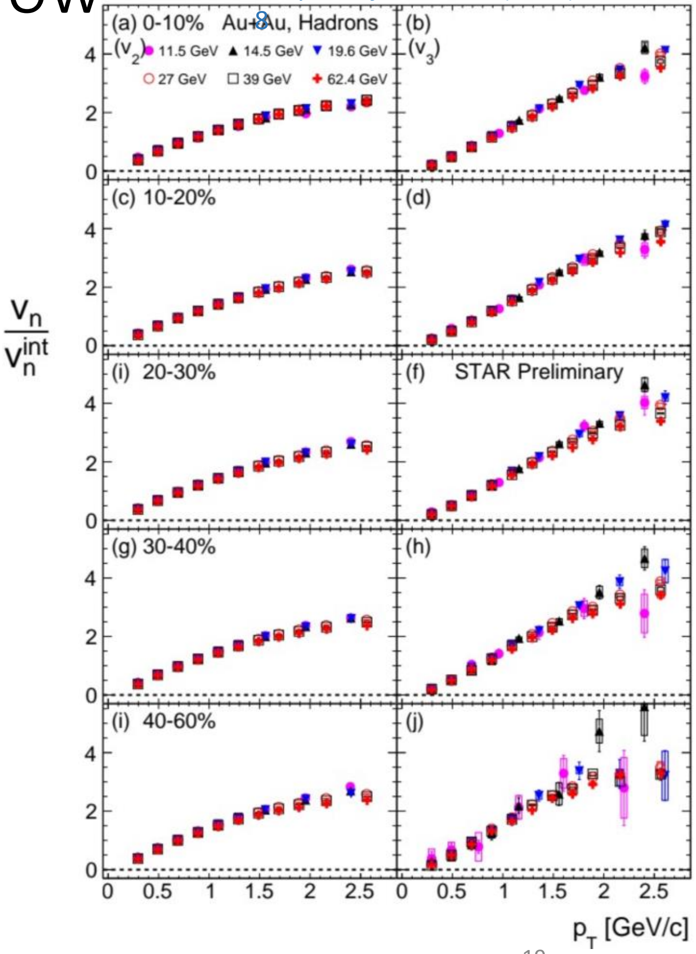


courtesy of R.A. Lacey

Scaling with integral anisotropic flow

J.Phys.Conf.Ser. 1690 (2020) 1, 01212



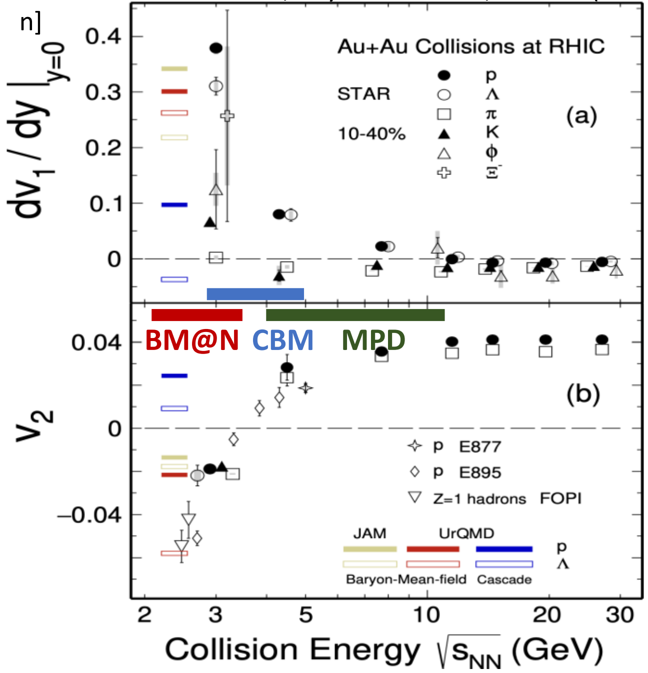


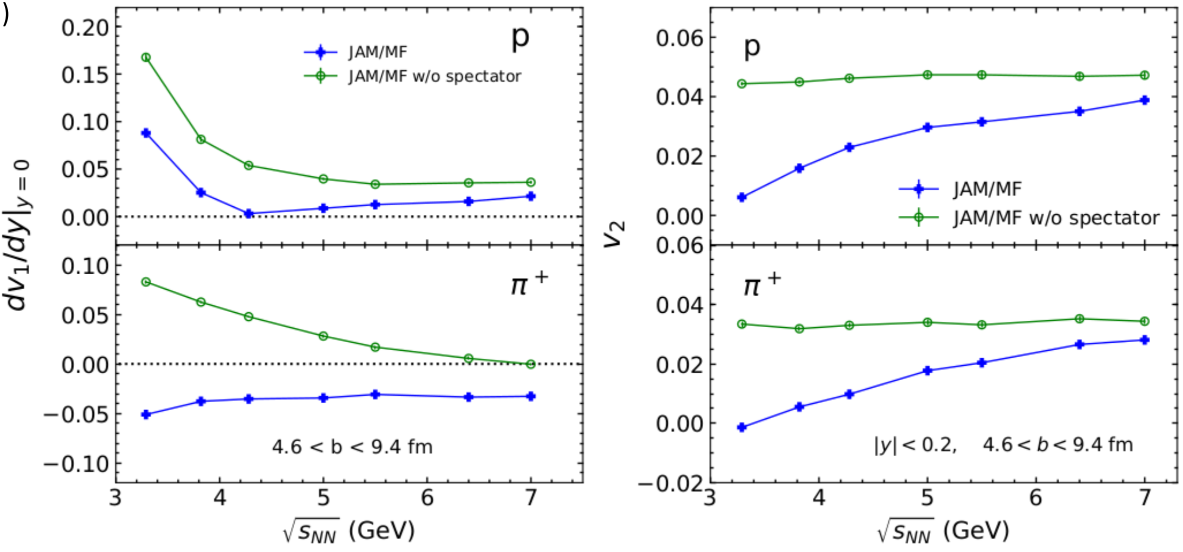
$$v_n(int.) \equiv \left|v_n^{int}\right| = \left|\langle v_n(p_T, y, \text{centrality}, \text{PID})\rangle_{p_T,y}\right|$$

- Scaling works at top RHIC and BES energy range
- Similar trend for pions, kaons and protons

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)

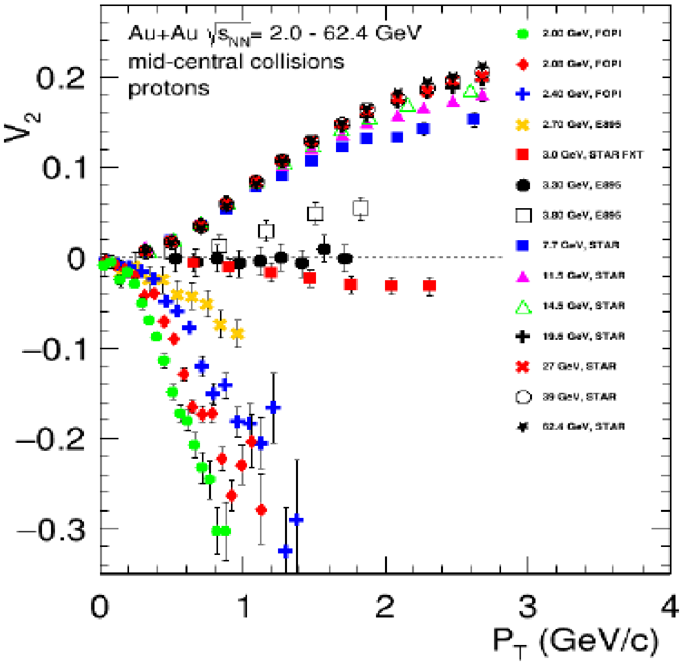
Anisotropic flow at FAIR/NICA energies is a delicate balance between:

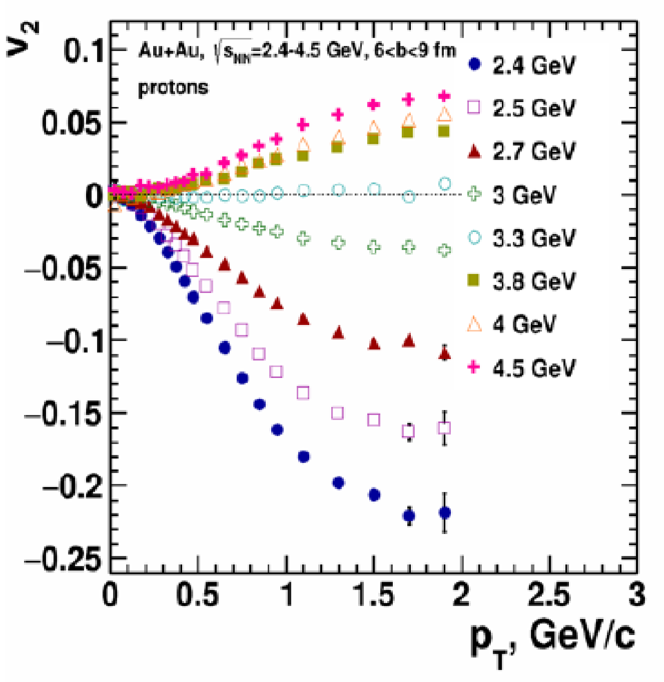
I. The ability of pressure developed early in the reaction zone ($t_{exp} = R/c_s\, , c_s = c\sqrt{dp/d\varepsilon}$) and

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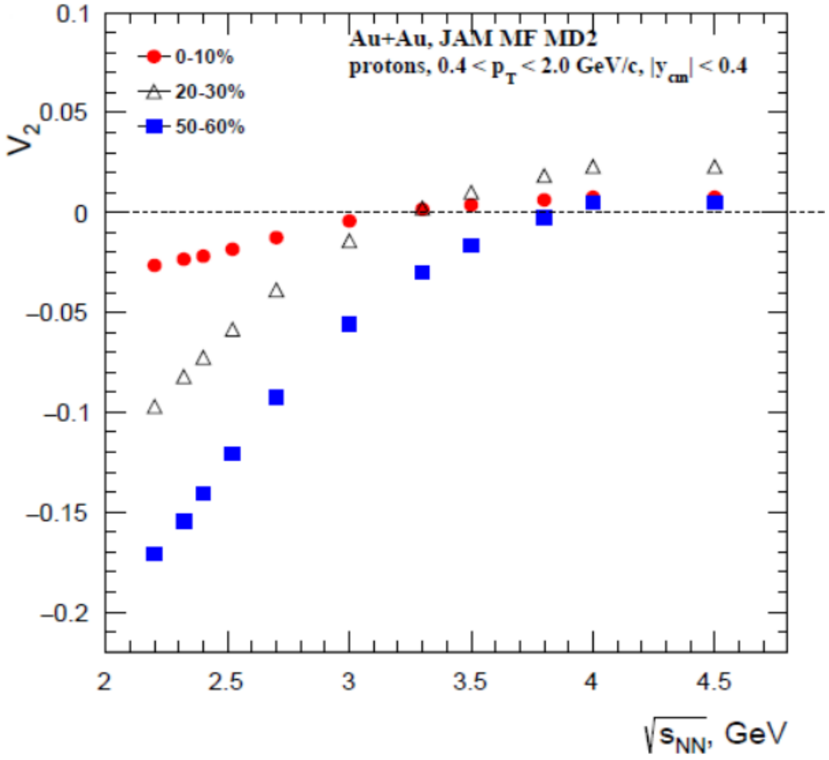
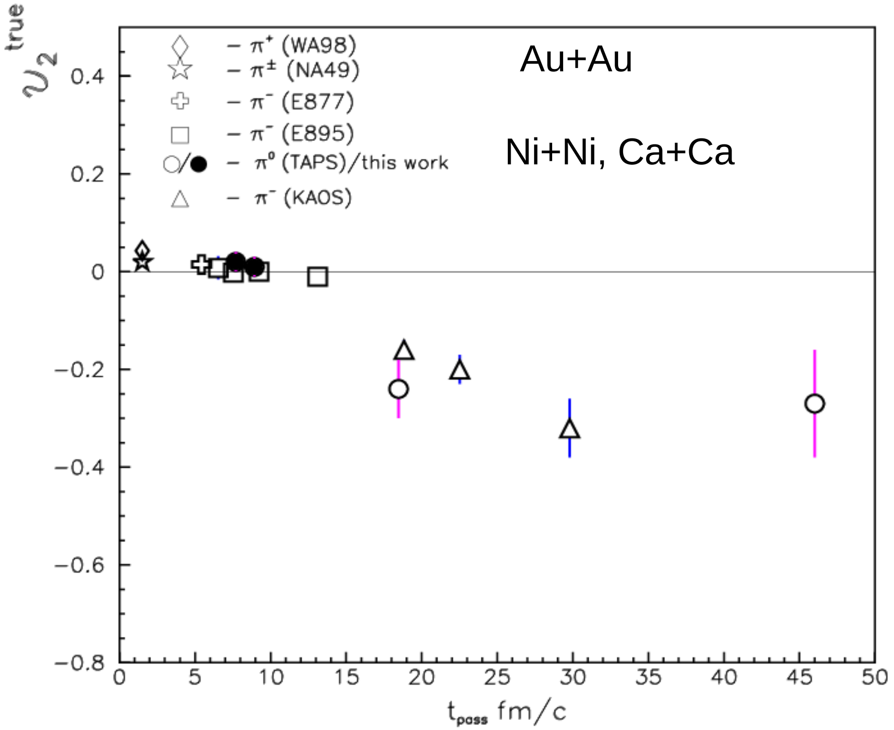
Elliptic flow: transition from out-of-plane to in-plane: geometry

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



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

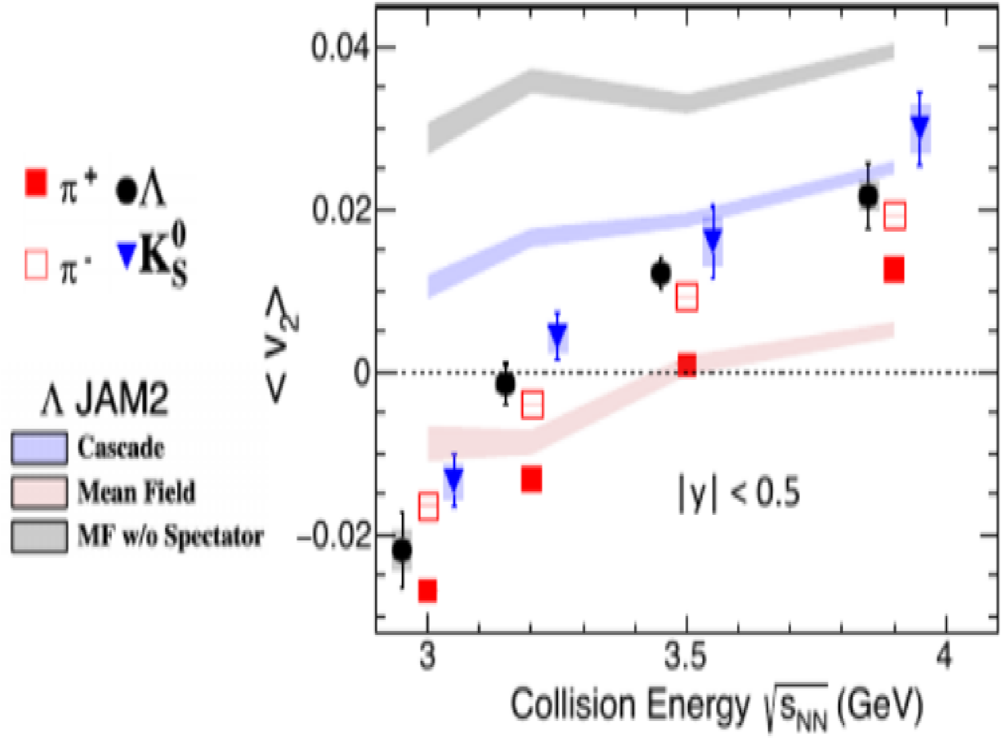


Au+Au

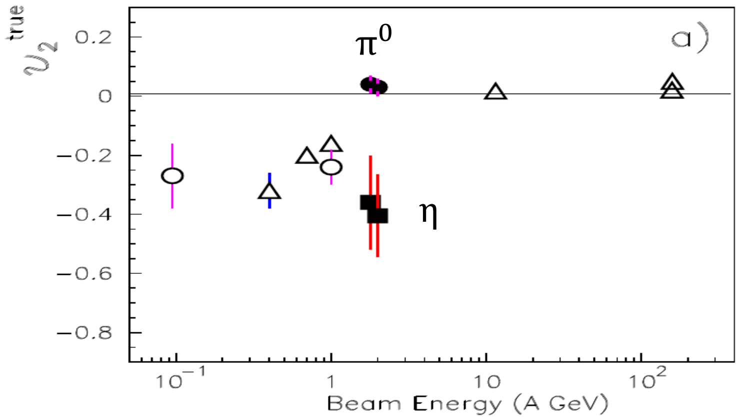
Ni+Ni, Ca+Ca

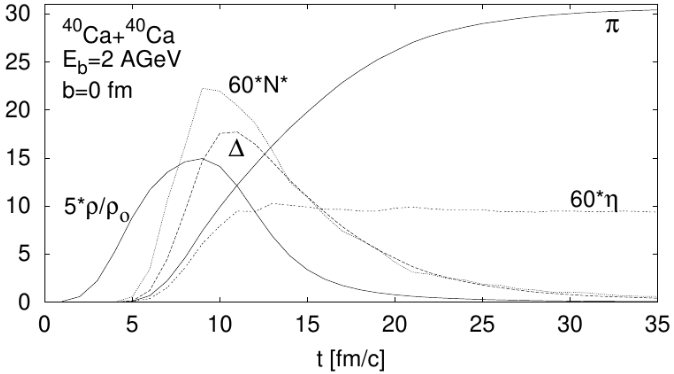
Elliptic flow: transition from out-of-plane to in-plane: PID

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



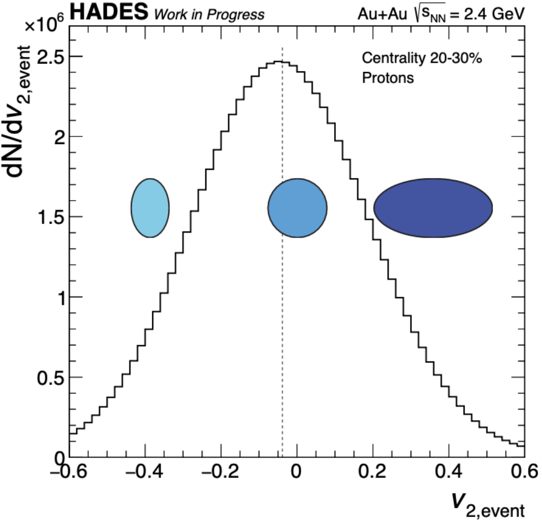
A.T Czech.J.Phys. 50S4 (2000) 139-166

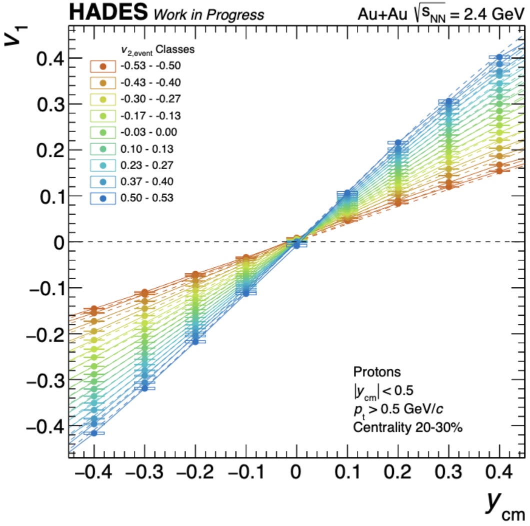


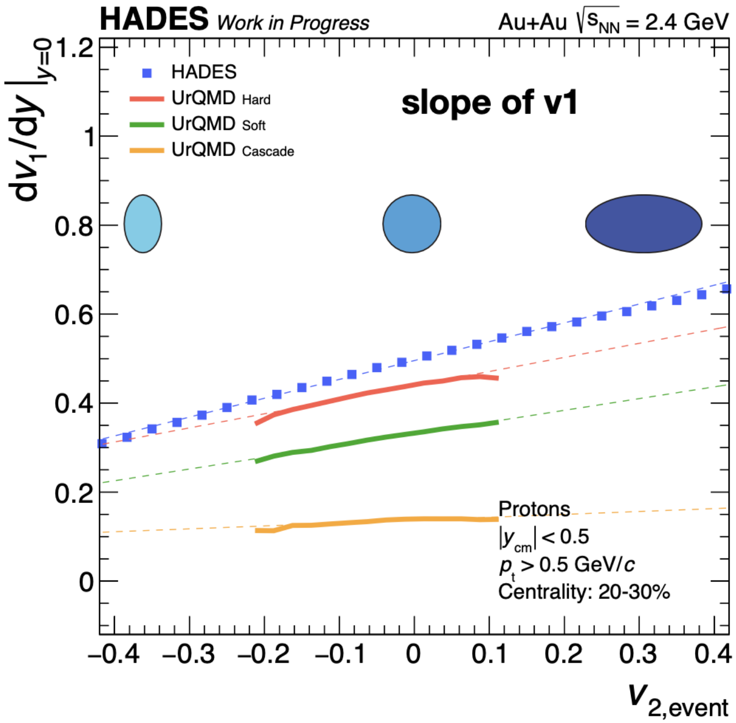


Event-wise flow correlations

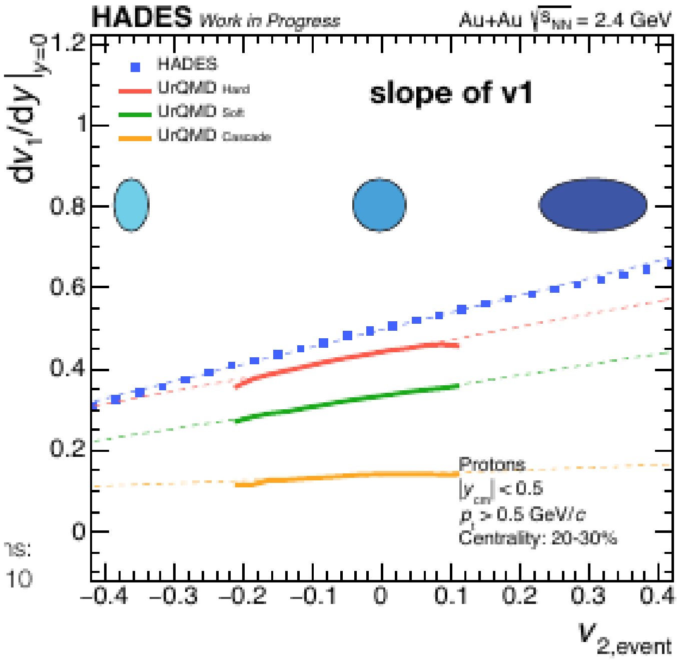
B. Kardan, EMMI Workshop 2024







- Events can be characterized based on the event-wise magnitude of the elliptic flow $v_{2,event}$
- UrQMD can not discribe $dv_1/dy|_{y=0}$ of protons as a function of $v_{2,event}$
- Strong sensitivity to the EOS



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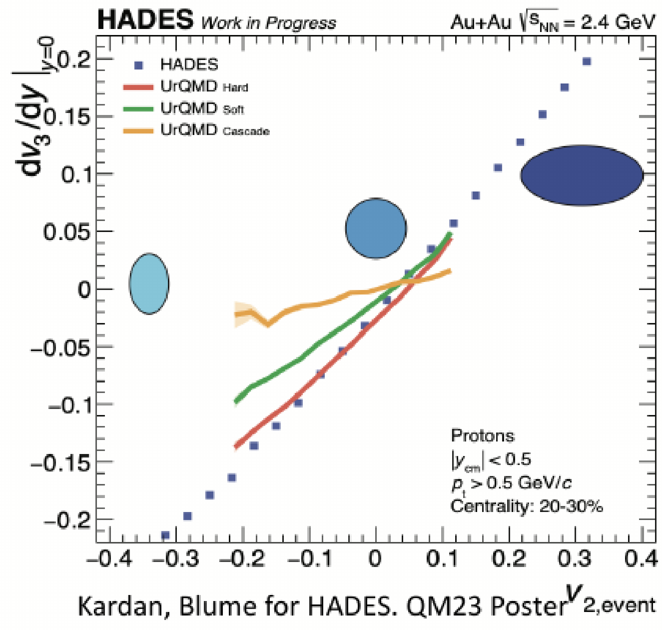
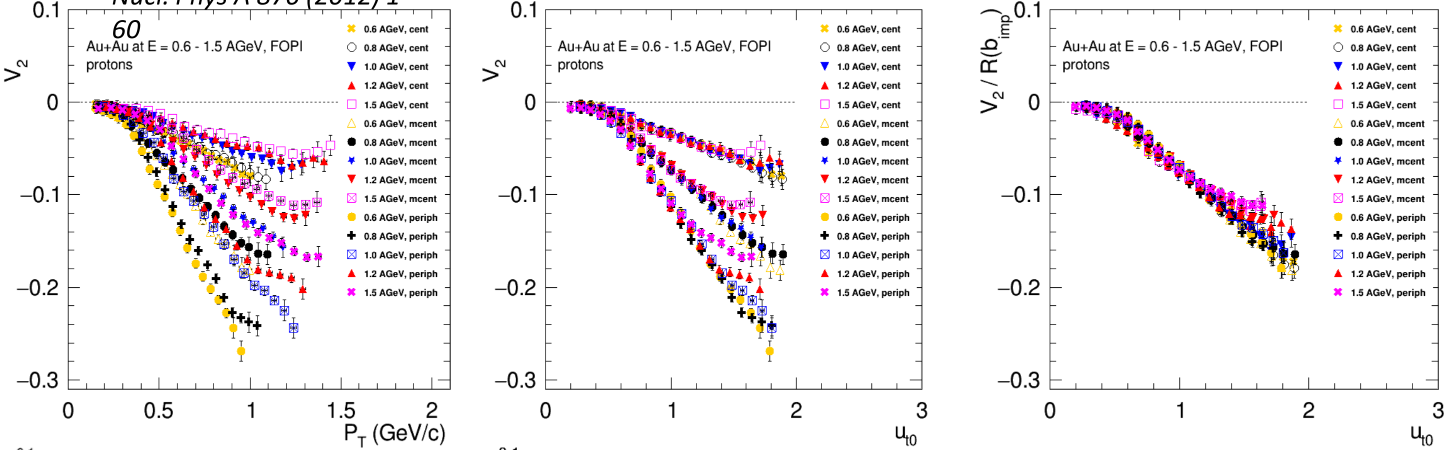


Kardan, Blume for HADES. QM23 Poster

New HADES results on flow correlations

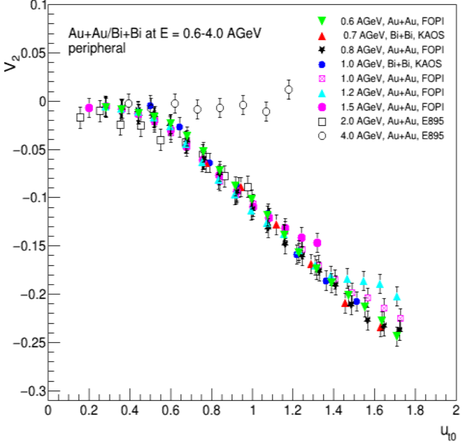
Scaling relations at SIS – scaling with passage time

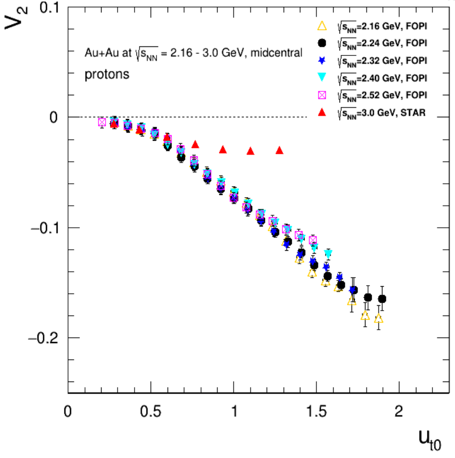
Nucl. Phys A 876 (2012) 1-60



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

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

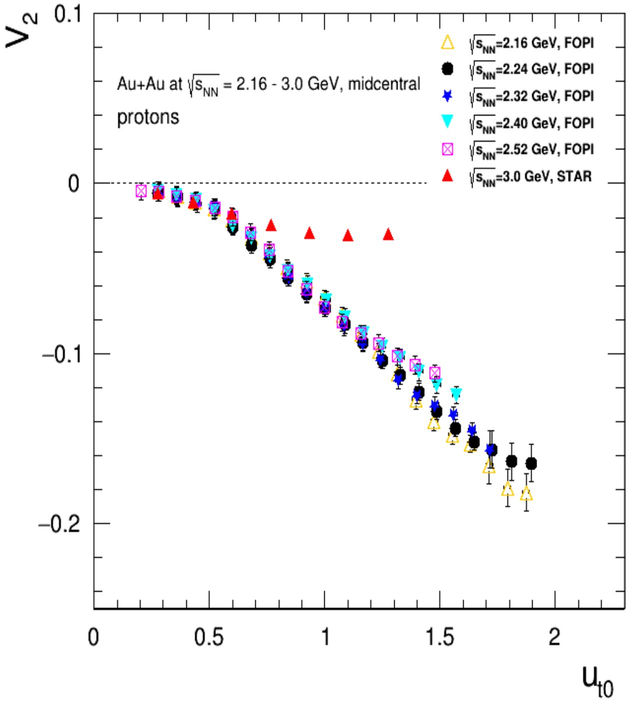


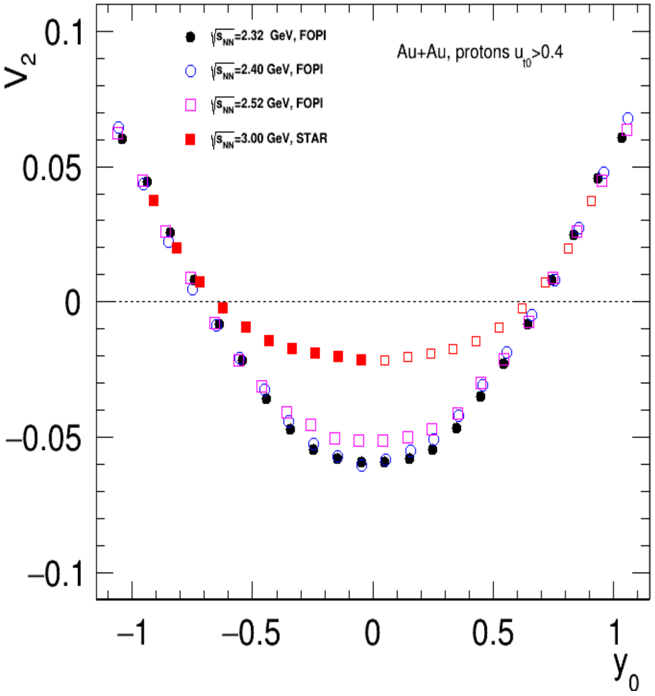


- The rather good scaling observed suggests that c_s does not change significantly over beam energy range $E_{kin} = 0.4 - 2$ AGeV ($\sqrt{s_{NN}} = 2 - 2.7$ GeV)
- Scaling breaks at $E_{kin} = 2.9$ AGeV ($\sqrt{s_{NN}} = 3$ GeV)

u_{t0} scaling: FOPI/STAR data

STAR published results for protons : Scaling breaks at $\sqrt{s_{NN}}$=3GeV – but holds at forward rapidity?

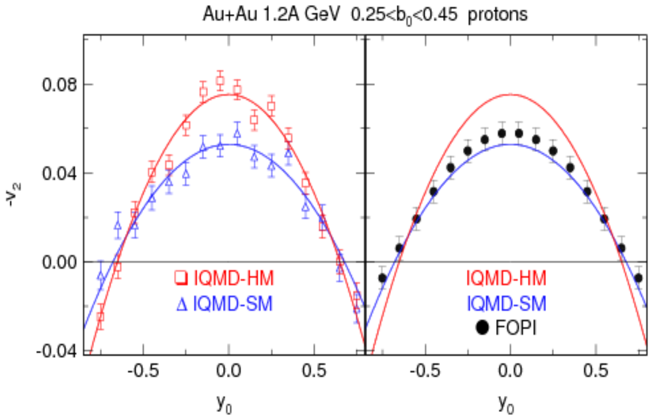


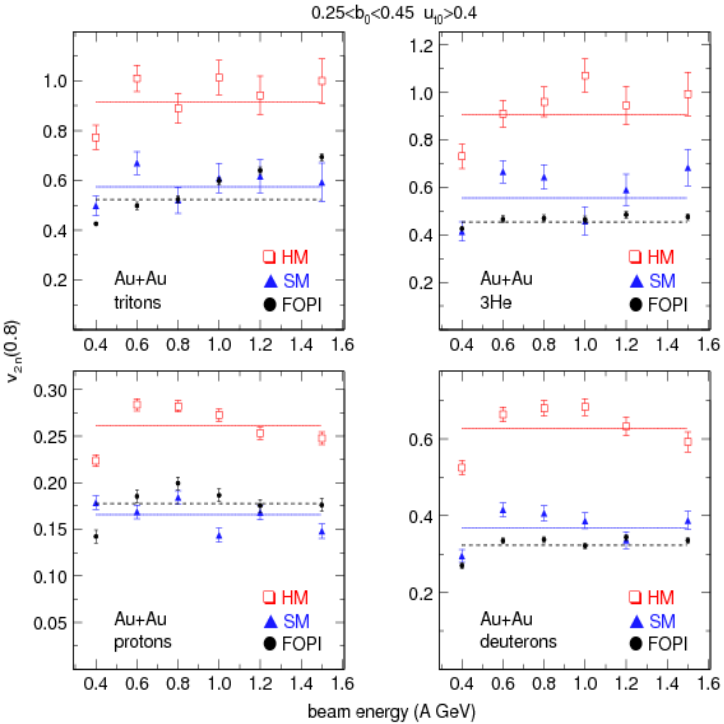


Rapidity dependence of v2 and EOS

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

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

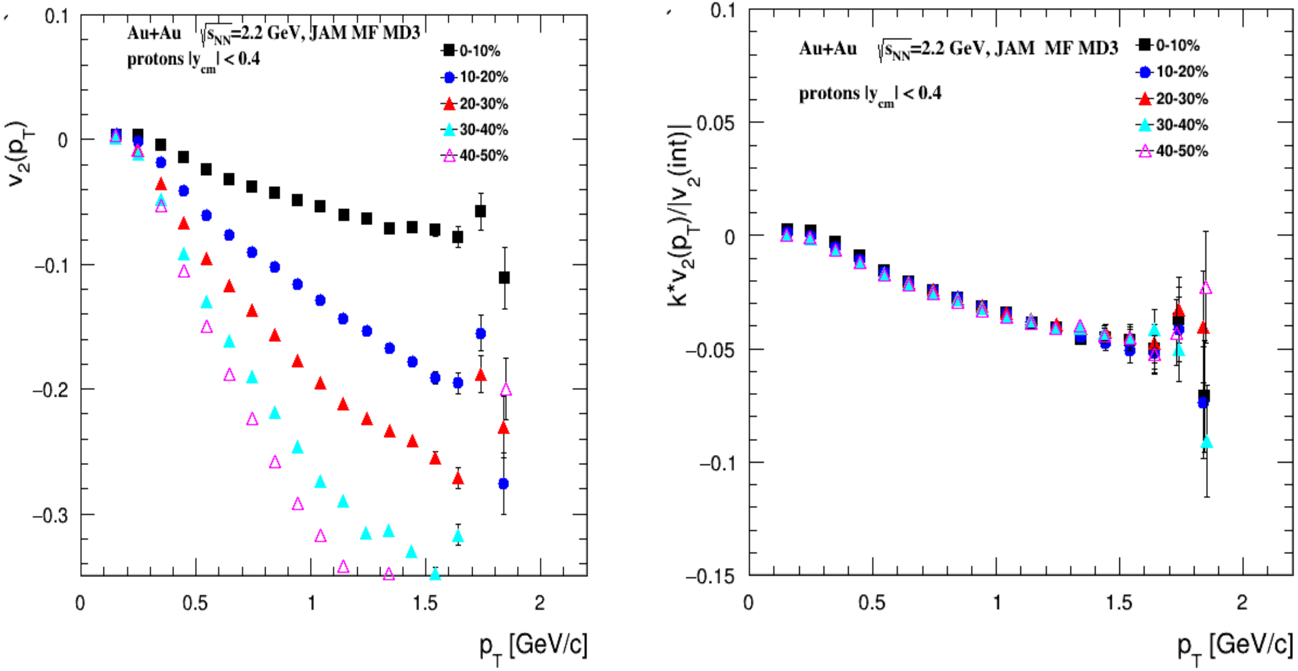




V2n=|V20|+|V22|
Fit: V2(y0)=V20+V22*Y0^2

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

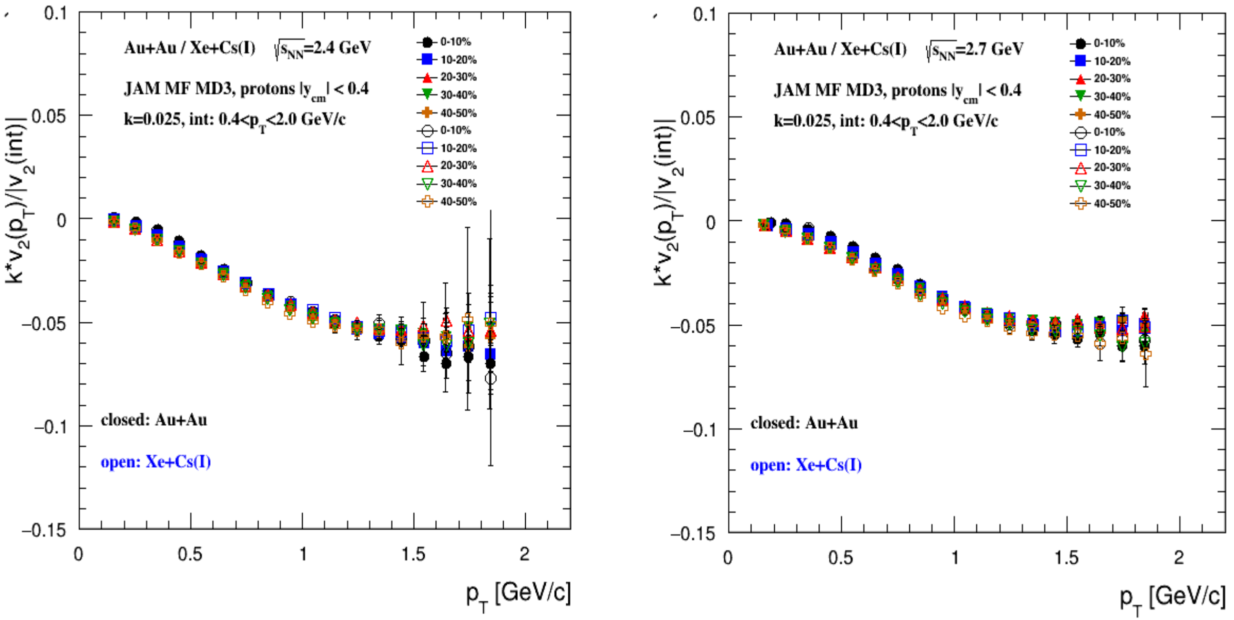
Scaling with integral flow of charged hadrons. Will it work at $\sqrt{s_{NN}}$ =2.2 GeV? (JAM mean field MD3)



In all plots k=0.025 and v2(int) for 0.4<pT<2.0 GeV/c

$$V_2(PID, p_T, centrality, \sqrt{s_{NN}}) = V_2(h, centrality, \sqrt{s_{NN}})^* \, V_2(PID, p_T)???$$

Scaling with integral flow of charged hadrons. Will it work at $\sqrt{s_{NN}}$ =2.4 GeV for different colliding systems? (JAM mean field MD3)

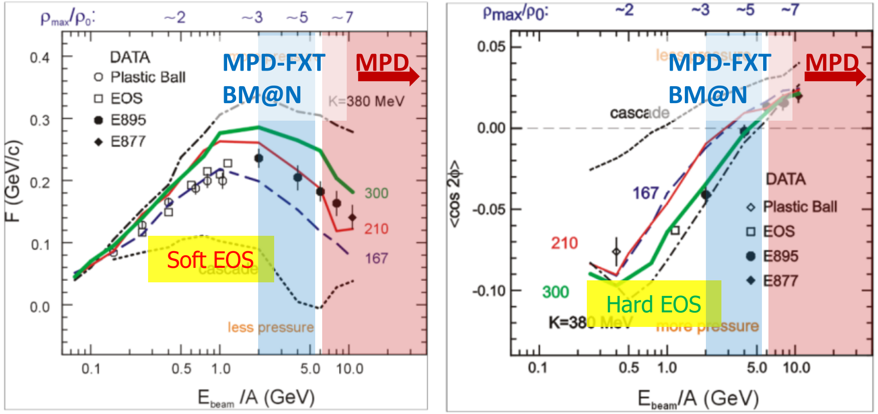


Scaling works for Au+Au and Xe+Cs(I) – general feature of the flow?

$$V_2(PID, p_T, centrality, \sqrt{s_{NN}}) = V_2(h, centrality, \sqrt{s_{NN}})^* V_2(PID, p_T)???$$

Sensitivity of the collective flow to the EOS

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



$$F = \left.\frac{d\langle p_x/A\rangle}{d(y/y_{\mathrm{cm}})}\right|_{y/y_{\mathrm{cm}}=1}$$

$$v_2 \equiv \langle \cos(2(\varphi - \Psi_{RP}))\rangle$$

Mean field usually can be defined using Skyrme potential with:

$$U(n_B) = A\left(\frac{n_B}{n_0}\right) + B\left(\frac{n_B}{n_0}\right)^{\tau}$$

Discrepancy in the interpretation:

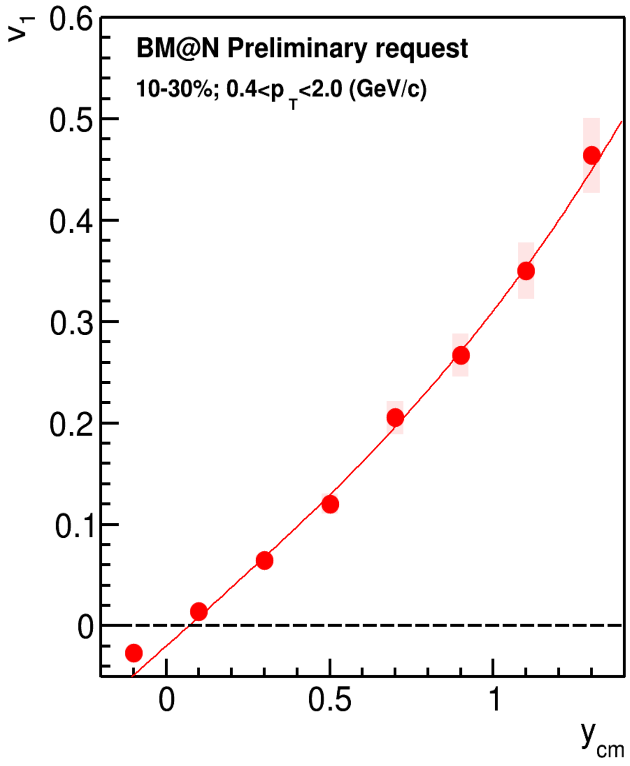
- v_1 suggests soft EoS
- v_2 suggests hard EoS

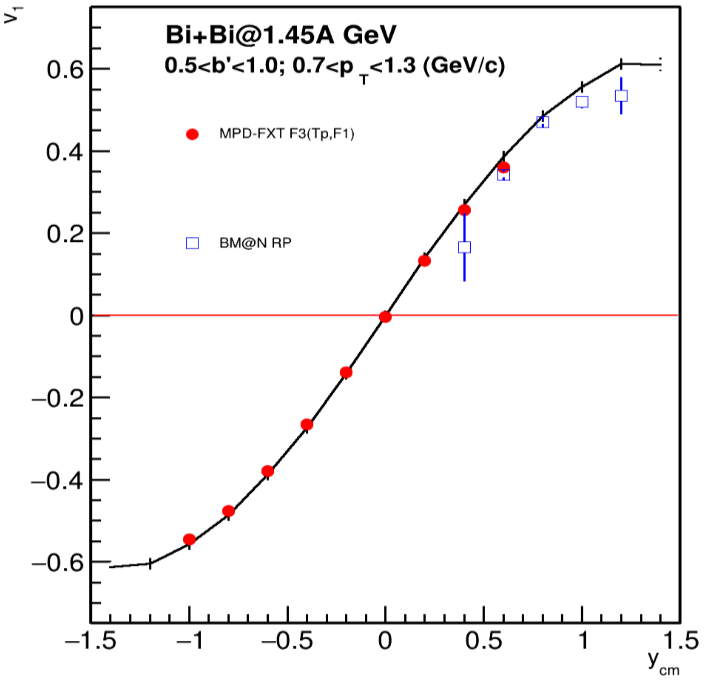
New measurements using new data and modern analysis techniques will address this discrepancy

More detailed model study should be done to address n_B-dependence of incompressibility K_0

Additional measurements are essential to clarify the previous measurements

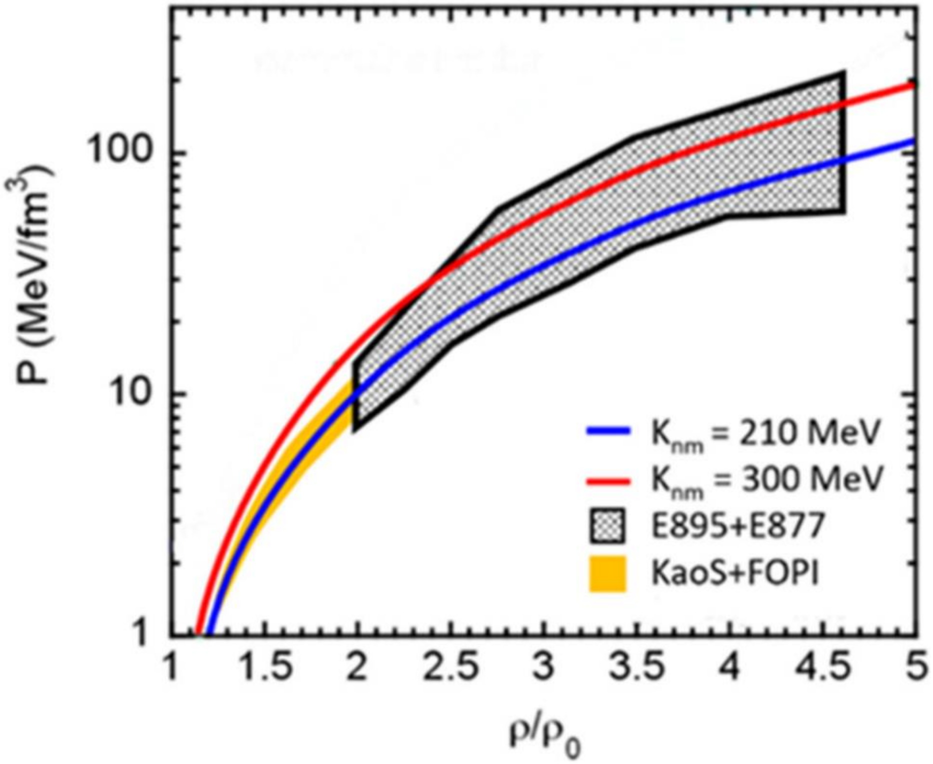
Directed flow of protons: BM@N – MD FXT

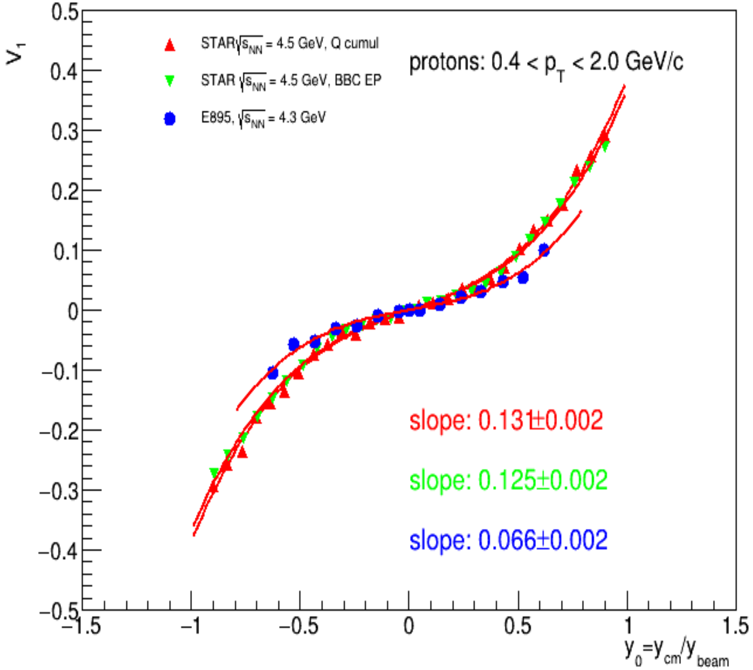




Please see Mikhail Mamaev talk at the workshop

Directed flow / Elliptic flow of protons: EOS





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**

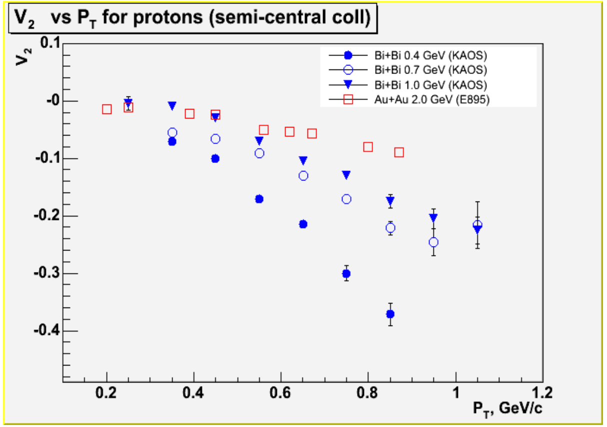
- **Feasibility study for anisotropic flow in MPD/MPD FXT/ BM@N:**

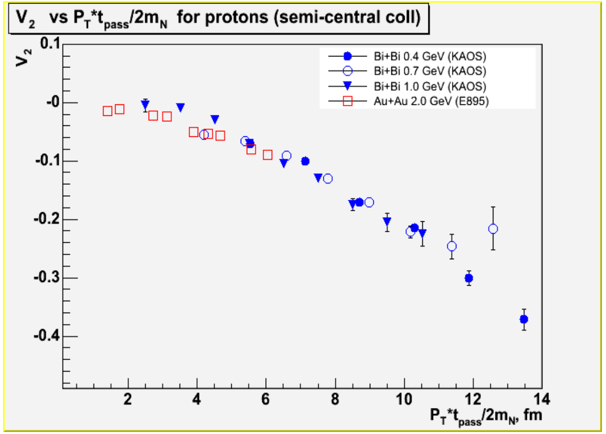
- Programs for flow analysis are available for MPD/BM@N collaborations – first preliminary flow results from BM@N will be published soon.

Backup

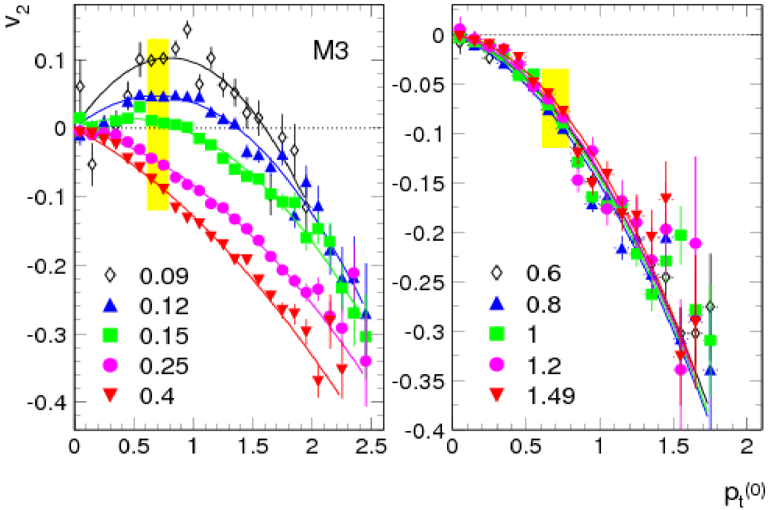
v_2 Flow at SIS-AGS: scaling relations

(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

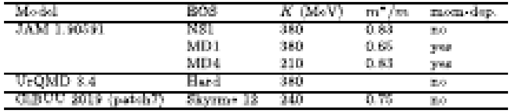
Determination of EOS

New level of precision - multi differential

Additional information from higher orders

Models:

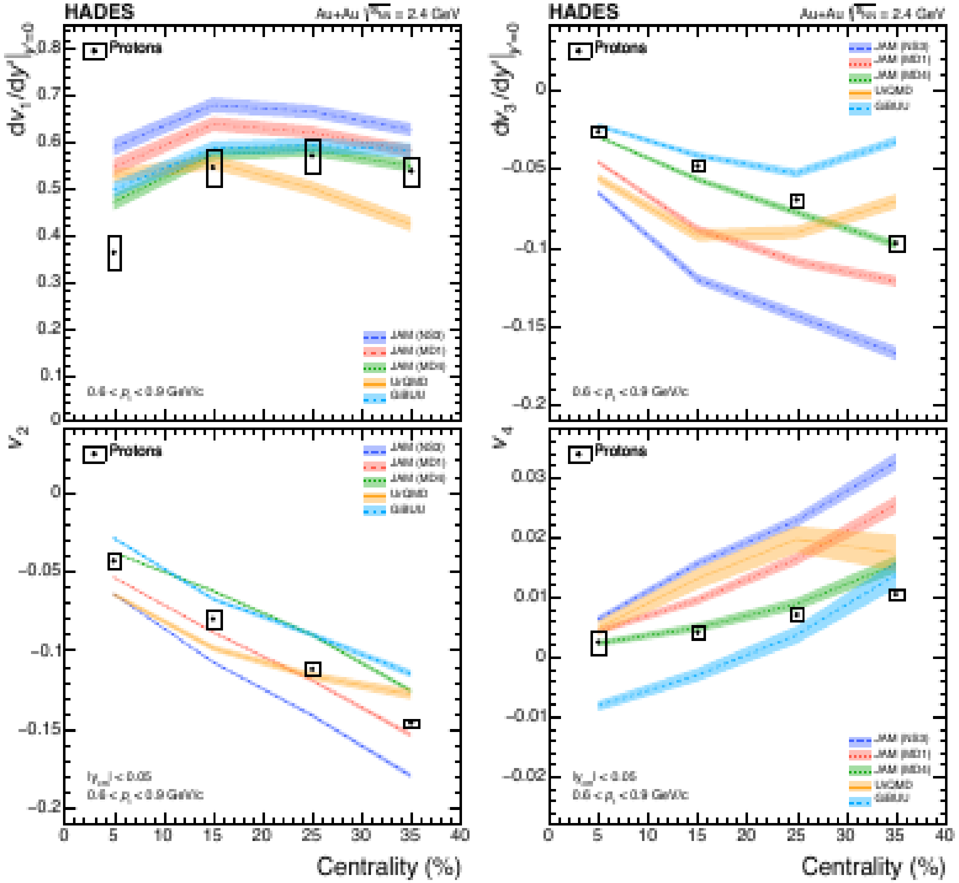
JAM 1.9 NS3 (hard EOS, mom.-indep.)
JAM 1.9 MD1 (hard EOS, mom.-dep.)
JAM 1.9 MD4 (soft EOS, mom.dep.)
UrQMD 3.4 (hard EOS, mom.-indep.)
GiBUU Skyrme 12 (soft EOS)



Model	EOS	K (MeV)	m^*/m	mom-dep.
JAM 1.90591	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

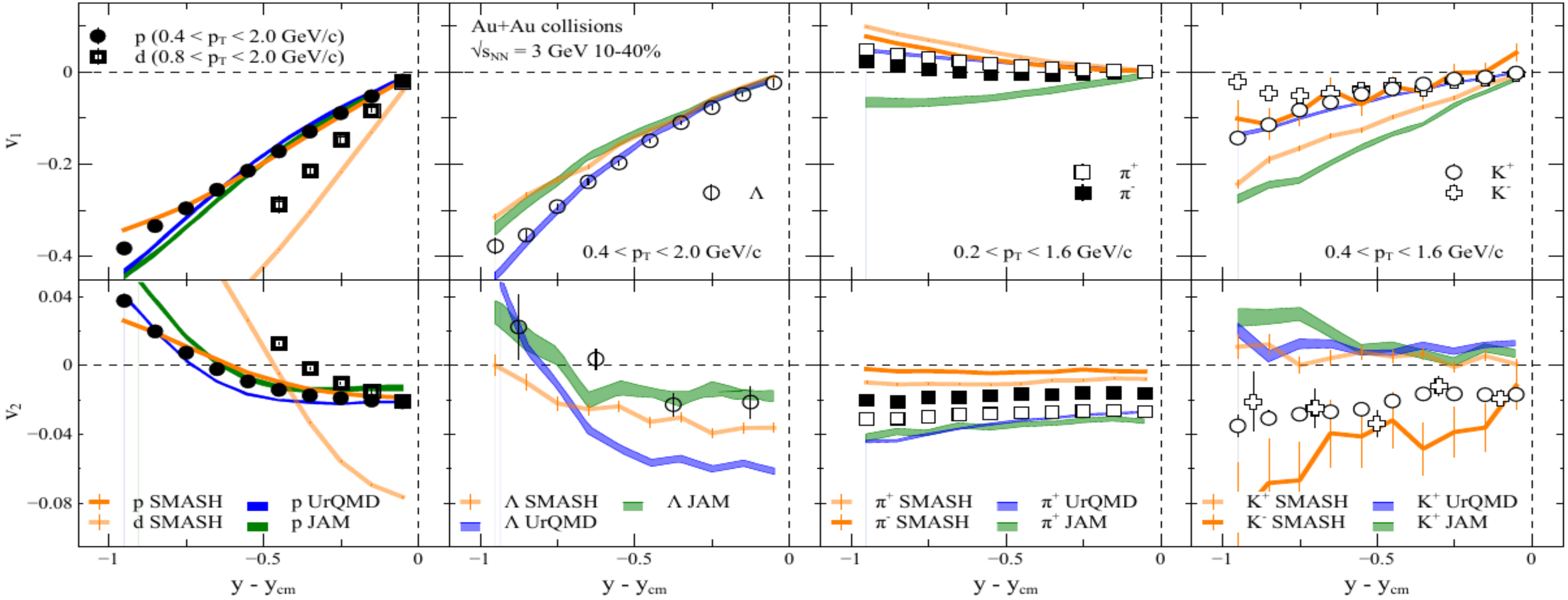
Conclusions

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