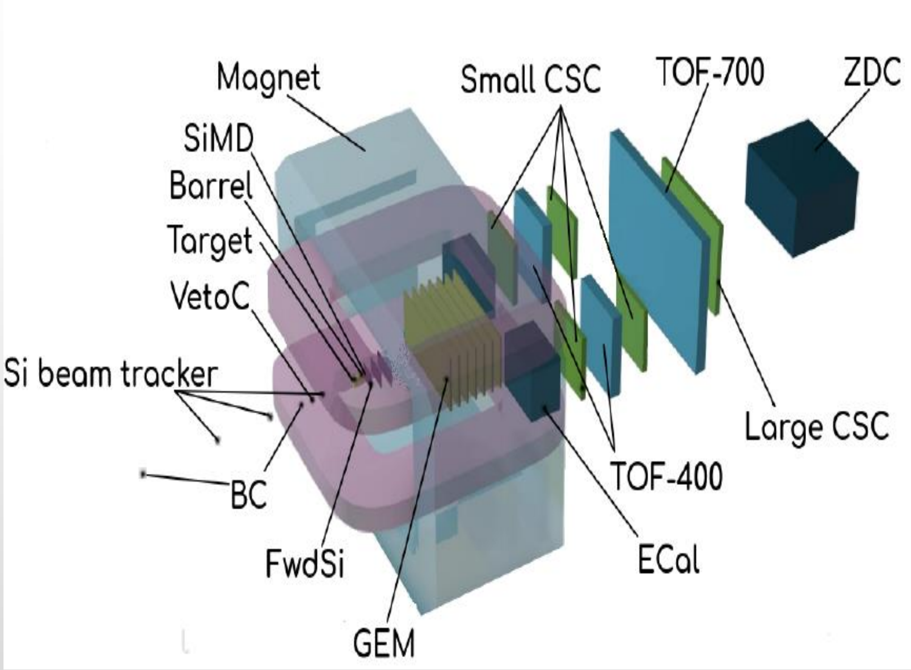
Review of existing results on the measurement of flows at the BM@N energy range and

what new measurements are needed

Arkadiy Taranenko (NRNU MEPhI)



9th BM@N Collaboration meeting, JINR, Dubna, 13-16 September, 2022

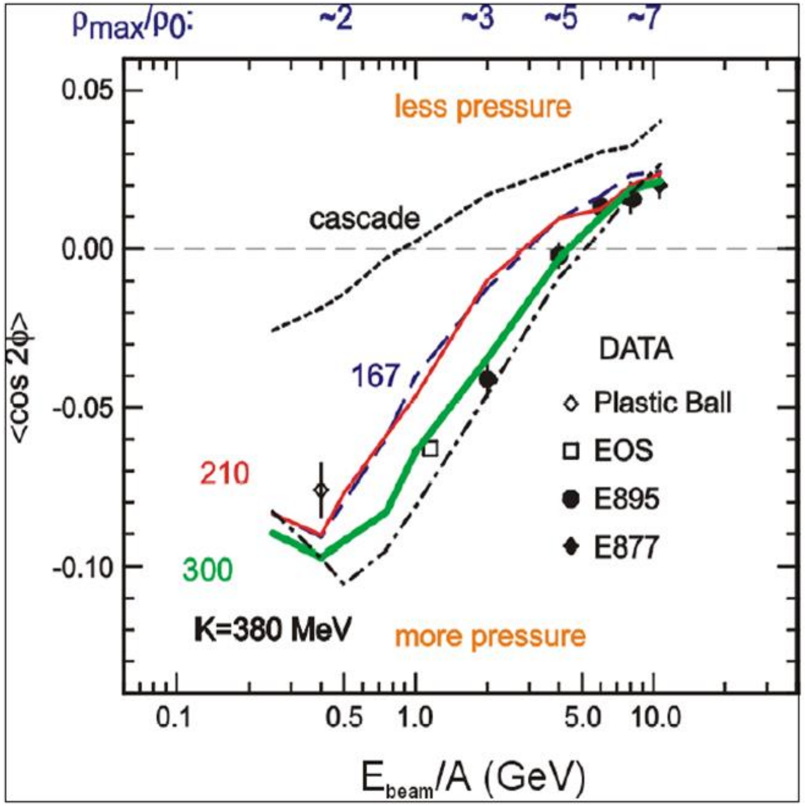
In collaboration with

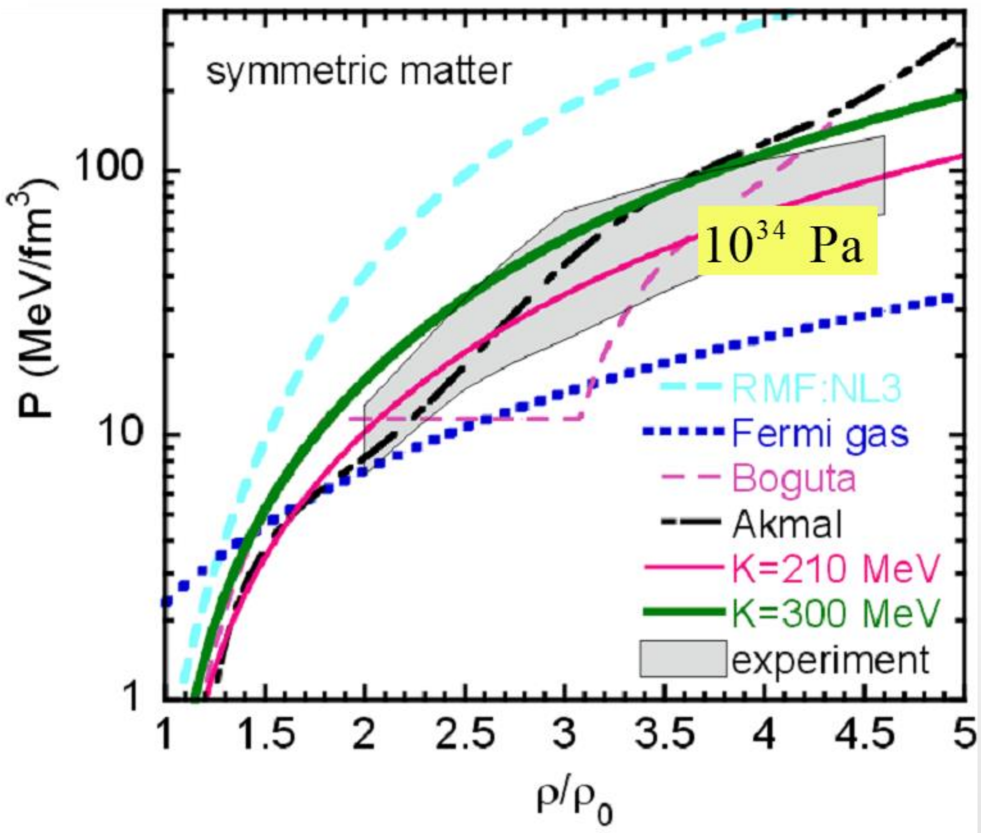
- ✓ Petr Parfenov
- ✓ Alexander Demanov
- ✓ Mikhail Mamaev
- ✓ Ilya Segal
- ✓ Dim Idrisov
- ✓ Valery Troshin
- ✓ Oleg Golosov

Analysis of data from STAR(RHIC), NA61/SHINE(CERN), HADES(SIS18) HIC experiments
Performance for Flow Measurements with BM@N and MPD experiments at Nuclotron-NICA

Flow at 2-5 GeV: Constraints for the Hadronic EOS

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





Passage time: **2R/($\beta_{cm}\gamma_{cm}$)**
Expansion time: **R/c_s**
$c_s = c\sqrt{dp/d\varepsilon}$ - speed of sound

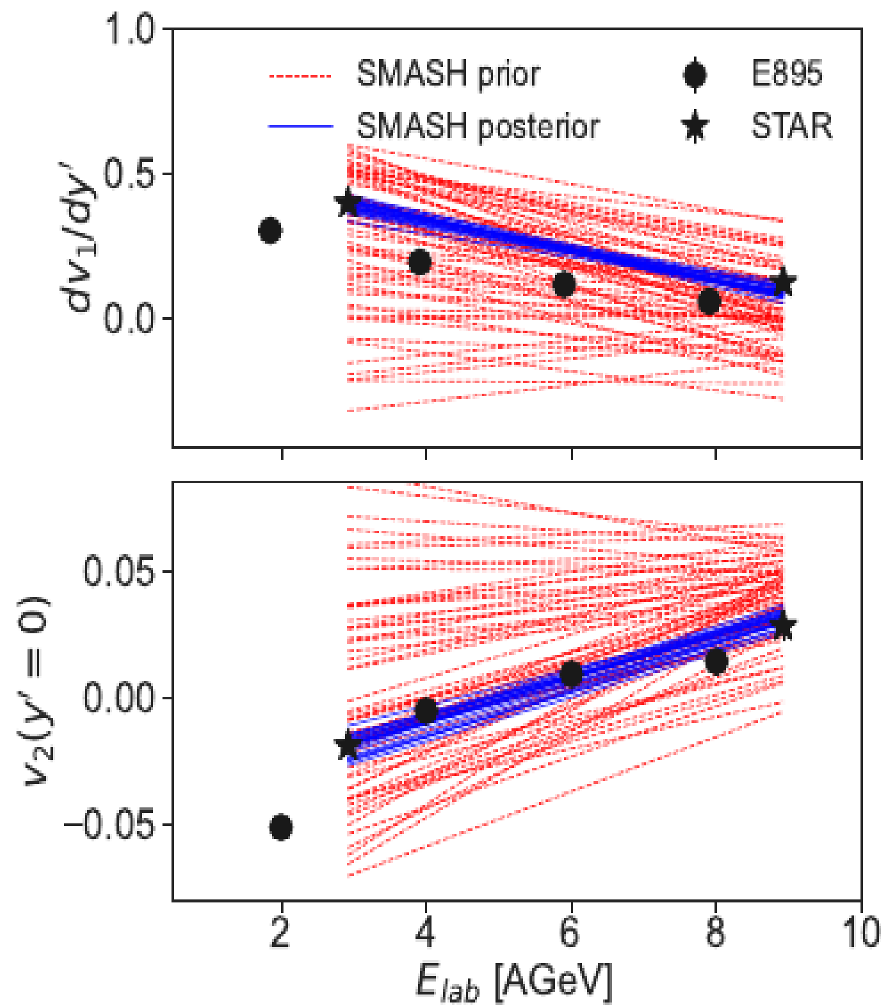
$$c_s = \sqrt{K/9m_N} \approx 0.15c, 0.21c$$

Flow at AGS/Nuclotron = Interplay of passage/expansion times

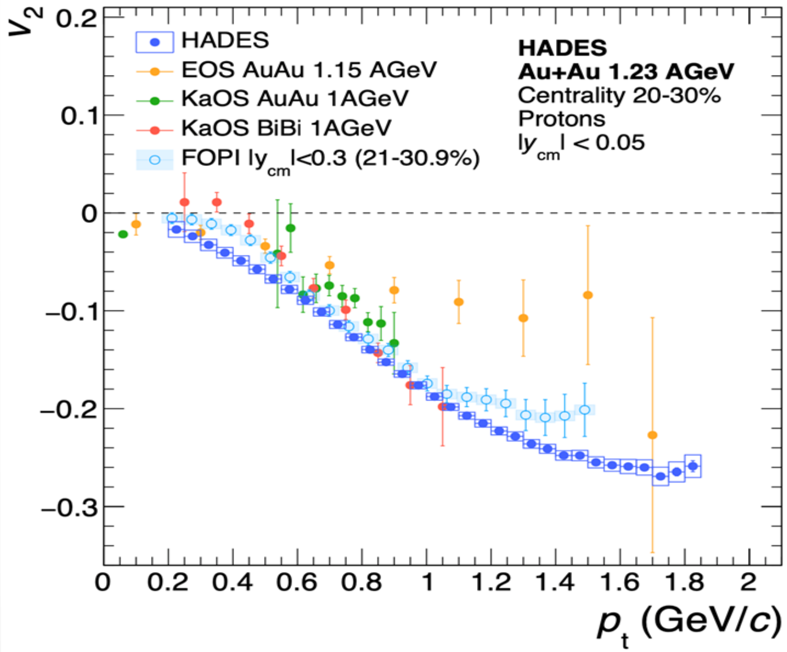
Flow at 2-5 GeV: Constraints for the Hadronic EOS

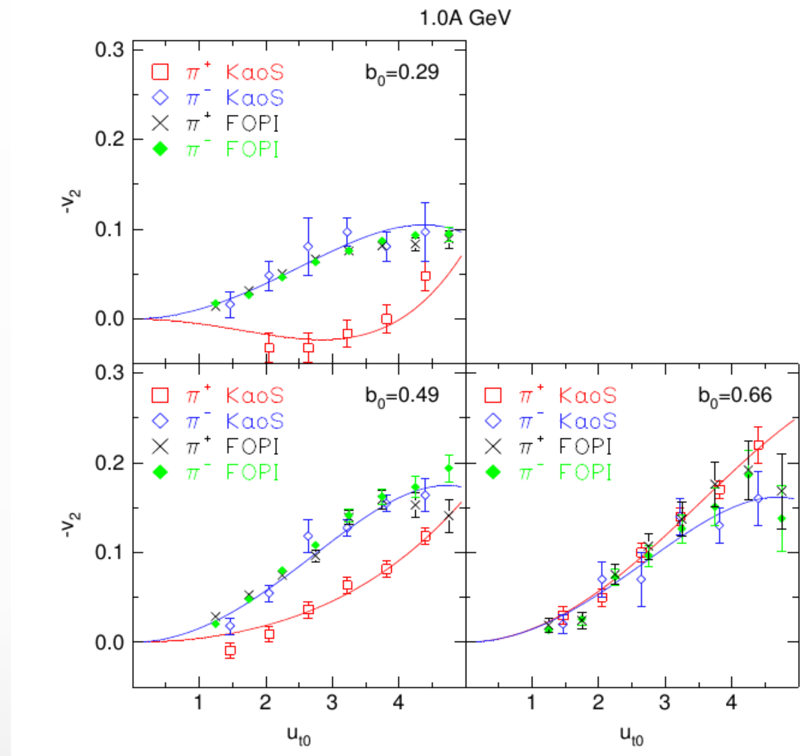
Sensitivity of Au+Au collisions to the symmetric nuclear matter equation of state at 2 -- 5 nuclear saturation densities, https://arxiv.org/abs/2208.11996, D. Oliinychenko, A. Sorensen, V. Koch, L. McLerran

- Flow observables at $\sqrt{s_{\rm NN}} \in [2.5, 5]$ GeV are very sensitive to the dense nuclear matter EOS at $n_B \in (2,4)n_0$. While lower densities can be studied by means of collisions at lower energies, there is almost no possibility to constrain the EOS at baryon densities $n_B > 4n_0$ from AA collisions, at least based on the analysis of flow observables. Similar conclusion was obtained in a concurrent UrQMD study [55].
- In particular, we find that the proton flow can yield a very tight constraint on the EOS, and an even better constraint can be obtained from the deuteron flow for which the sensitivity to the EOS is twice as large as that for protons. To a lesser extent, pion flow can also be used to help constrain the EOS.
- Even given a large freedom to vary the EOS differentially in different density regions, we cannot describe the E895 proton flow data: dv_1/dy' prefers a relatively soft EOS while $v_2(y' = 0)$ prefers a harder one. However, the more recent STAR data, which additionally seems to be in disagreement with the E895 data, can be described within our model, yielding $c^2_{[2,3]n_0} = 0.47 \pm 0.12$, $c^2_{[3,4]n_0} = -0.08 \pm 0.14$ and thus indicating a very hard EOS at $n_B \in (2,3)n_0$ and a possible phase transition at $n_B \in (3,4)n_0$.



Why do we need new measurements at BM@N?





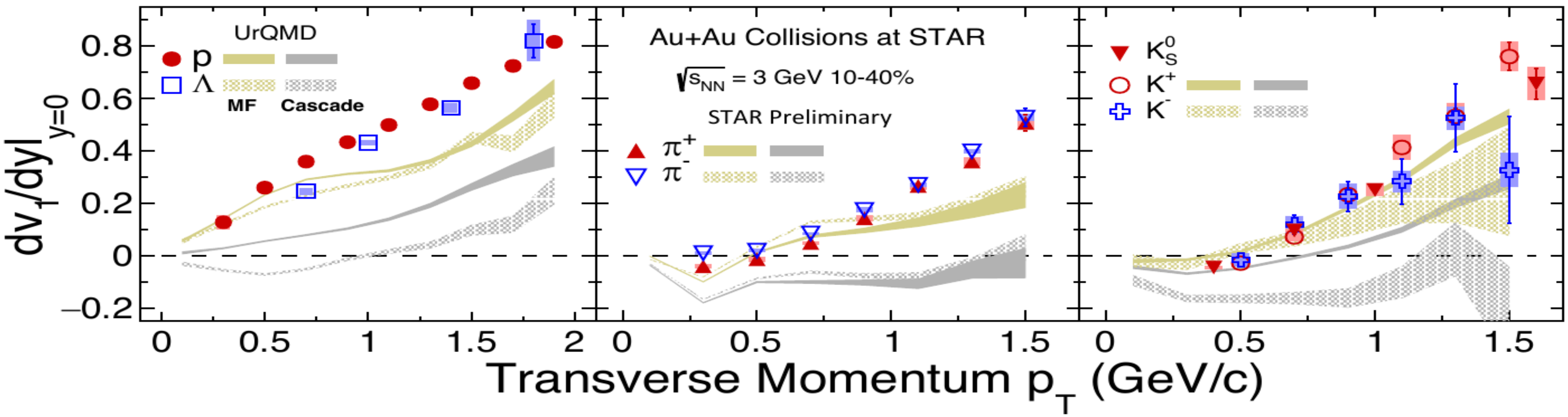
The main source of existing systematic errors in v_n measurements is the difference between results from different experiments at the same collision energy.

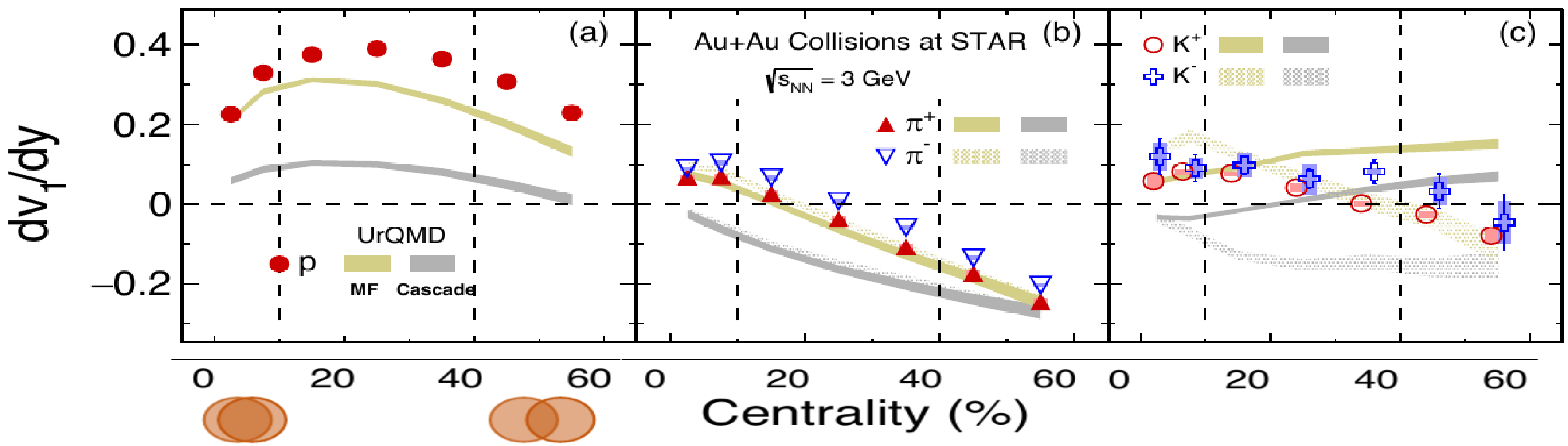
A good measurement should be reproducible; in particular, it should be done in such a way that one can easily compare results from different experiments, using different detectors.

For the sake of comparison with theory, an ideal measurement is a well-defined quantity that corresponds to a generic property of the system, closely related to an interesting theoretical concept.

"Eliminating experimental bias in anisotropic-flow measurements of high-energy nuclear collisions", Phys.Rev. C87 (2013) 4, 044907/Matthew Luzum, Jean-Yves Ollitrault

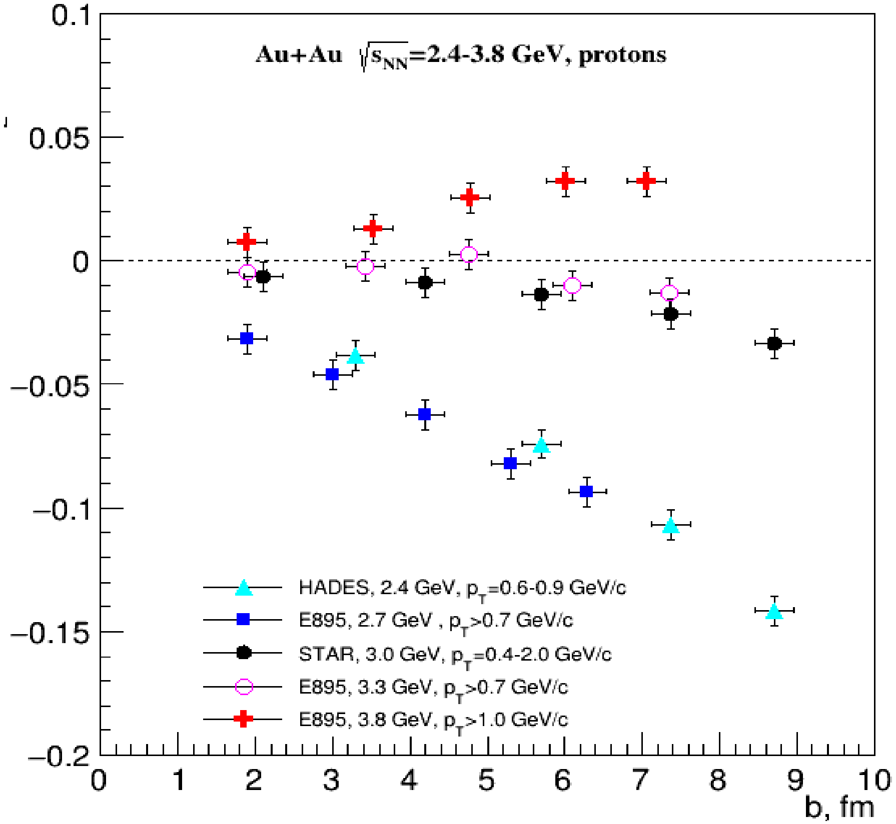
What should we know about the directed flow (v1) and slope at midrapidity from the existing data

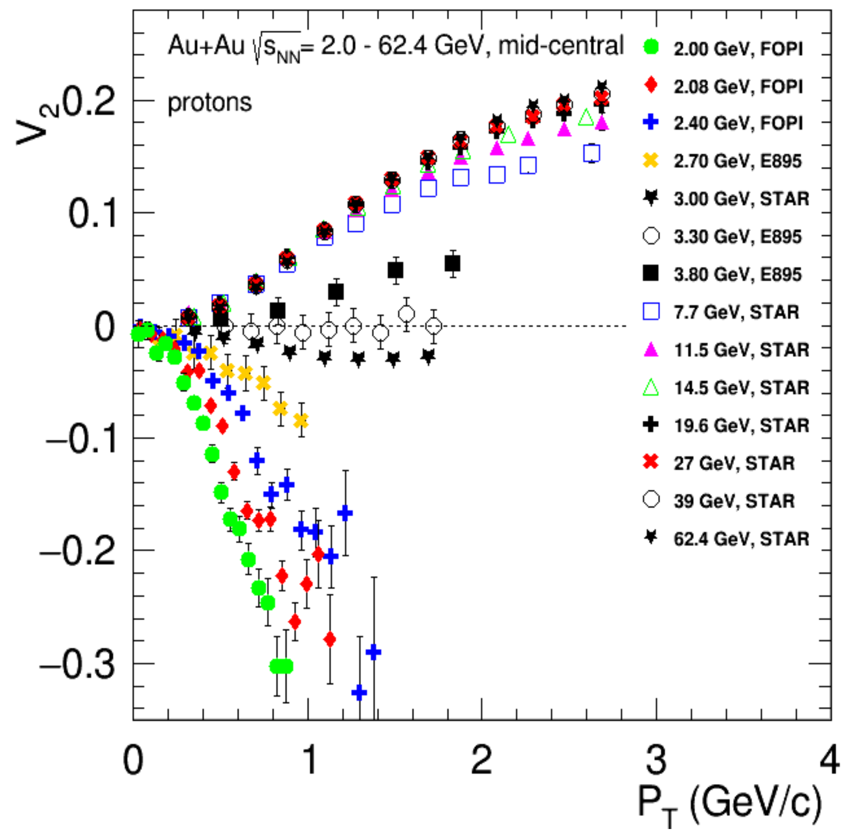




3 GeV (BES RHIC): Strong p_T dependence of the slope of directed flow (dV_1/dy) for identified particles. Modest centrality dependence for protons – make easy to make comparison between different experiments for midcentral collisions/

What should we know about the elliptic flow (v2) from the existing data

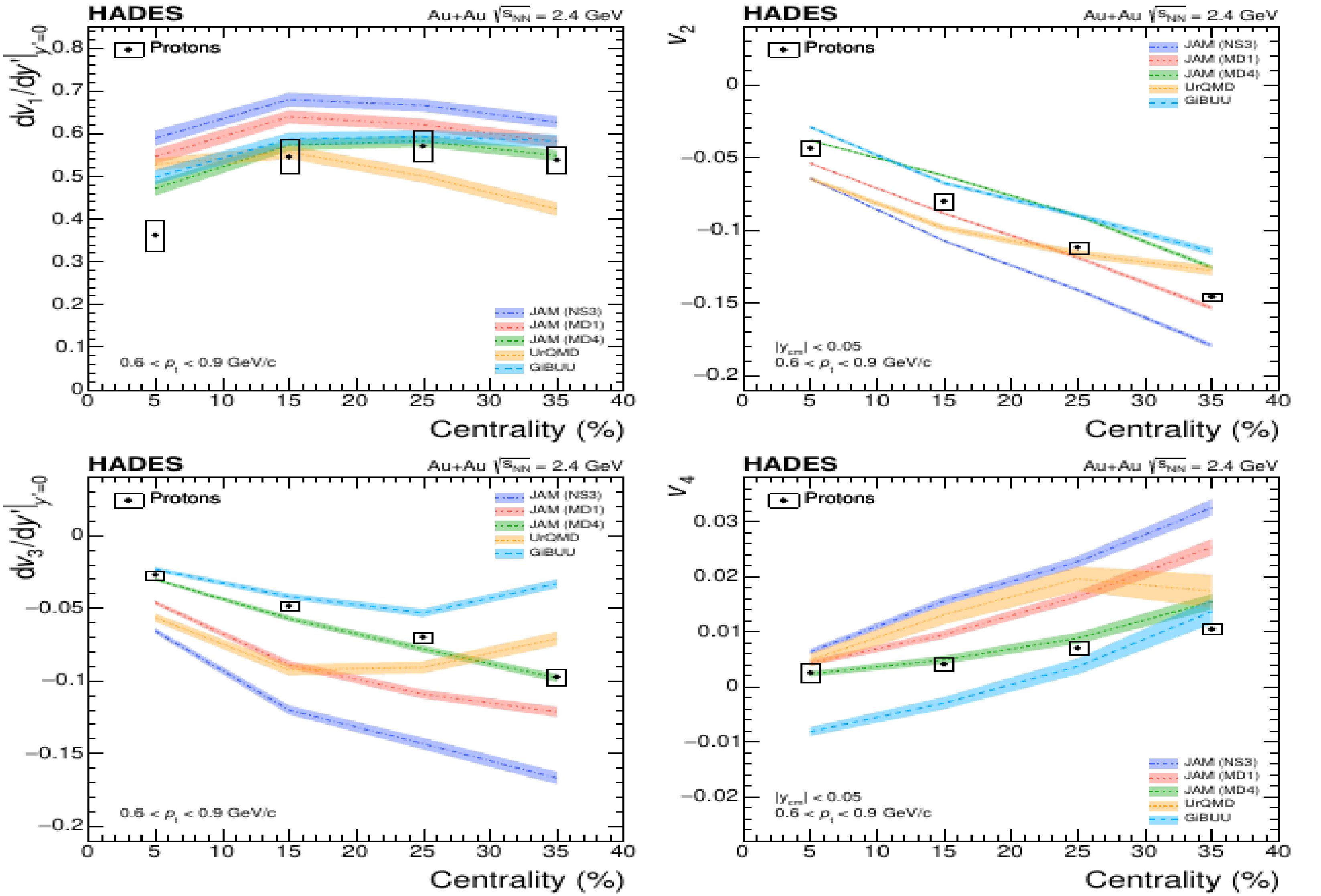




2-2.5 GeV (SIS): Strong p_T dependence of elliptic flow (V_2) for identified particles
Strong centrality dependence for protons – make difficult to make comparison between different experiments (change sign as a function of collision energy)

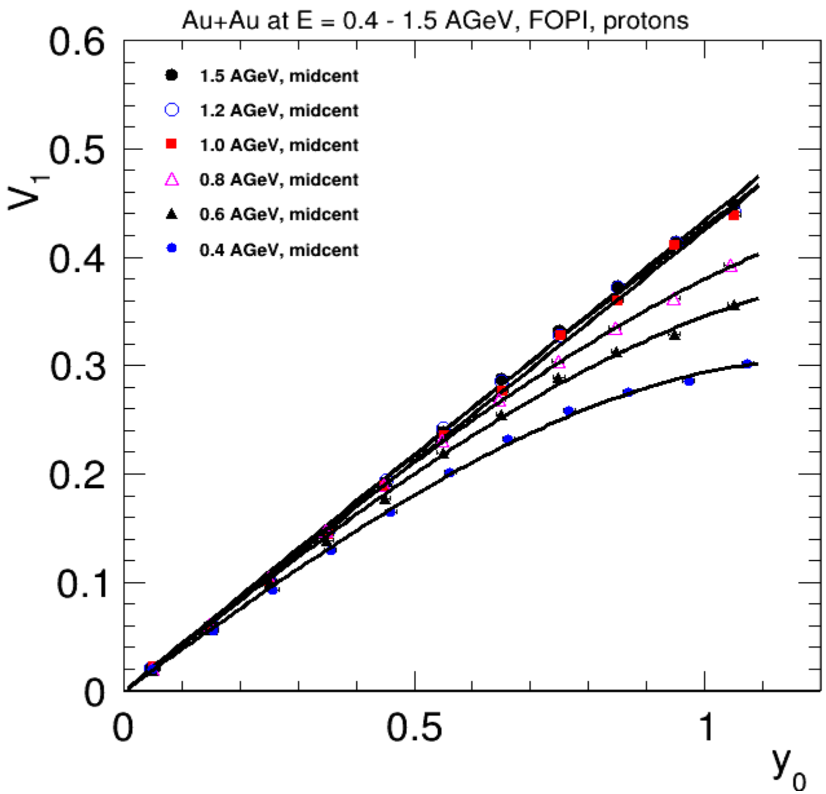
What should we know about the v3 and v4 from the existing data

HADES , https://arxiv.org/abs/2208.02740



(V_1) of protons and slope at midrapidity from FOPI (SIS)

Systematics of azimuthal asymmetries in heavy ion collisions in the 1 A GeV regime



FOPI experiment always presents data in the scaled variables and make cuts also for scaled variables: $y_0 = y_{cm}/ y_{beam}$ and u_{t0} (instead of p_T) - $u_{t0} = p_T / (m_0\beta_{cm}\gamma_{cm})$

Figure shows $V_1(y_0)$ for protons from midcentral Au+Au collisions (3.35-6.02 fm) with u_{t0}>0.4 cut

Looks like all experiments fit $V_1(y_0)$ = $v_{11} * y_0$ + $v_{13} * y_0^3$

mass and charge identified LCP in the high energy run. In these plots the abscissa is the longitudinal (beam axis) rapidity y in the $c.o.m.$ reference system and the ordinate is the transverse (spatial) component t of the four-velocity u, given by $u_t = \beta_t\gamma$. The 3-vector $\vec{\beta}$ is the velocity in units of the light velocity and $\gamma = 1/\sqrt{1-\beta^2}$. Throughout we use scaled units $y_0 = y/y_p$ and $u_{t0} = u_t/u_p$, with $u_p = \beta_p\gamma_p$, the index p referring to the incident projectile in the $c.o.m.$. In these units the initial target-projectile rapidity gap always extends from $y_0 = -1$ to $y_0 = 1$.

Nucl. Phys. A 876 (2012) 1-60

$\langle V_1 \rangle$ of protons and slope at midrapidity from FOPI (SIS)

Systematics of azimuthal asymmetries in heavy ion collisions in the 1 A GeV regime

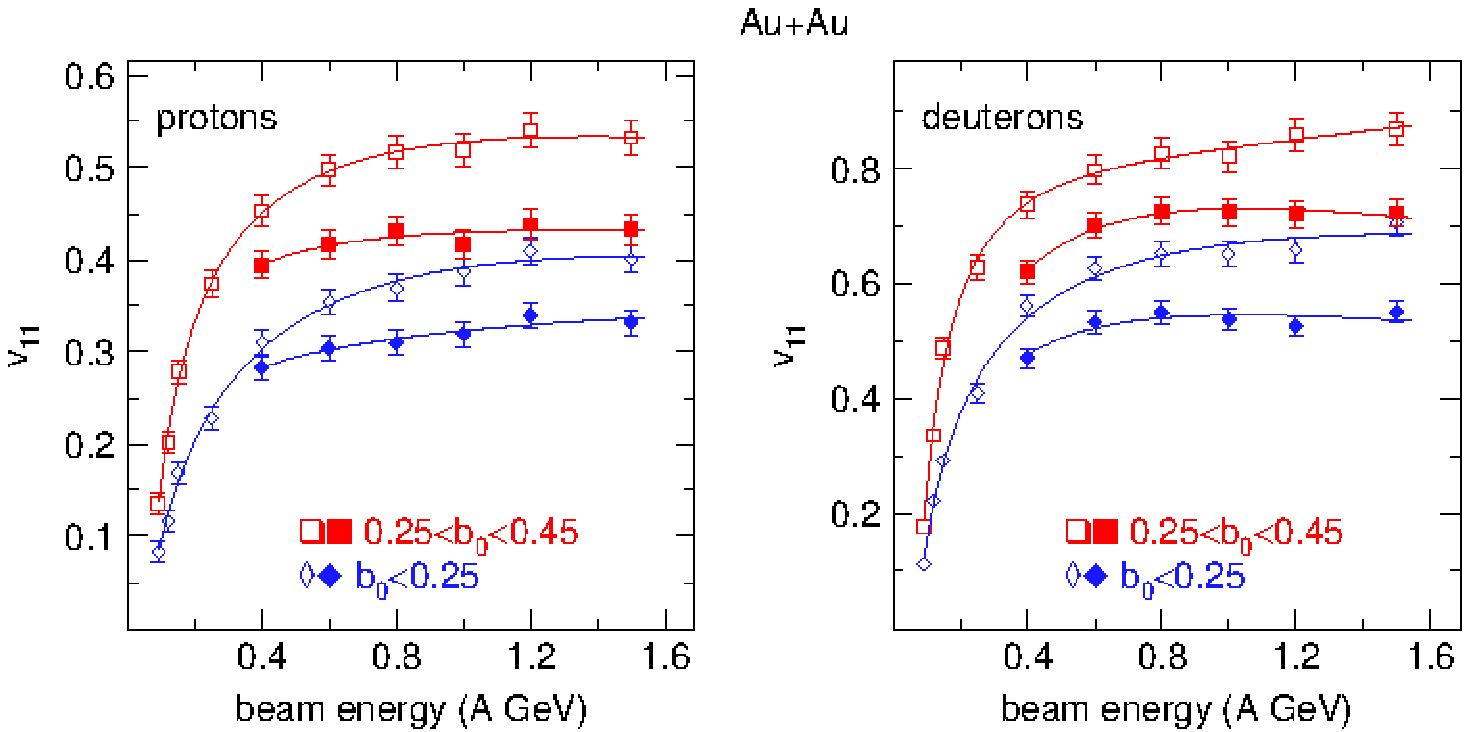
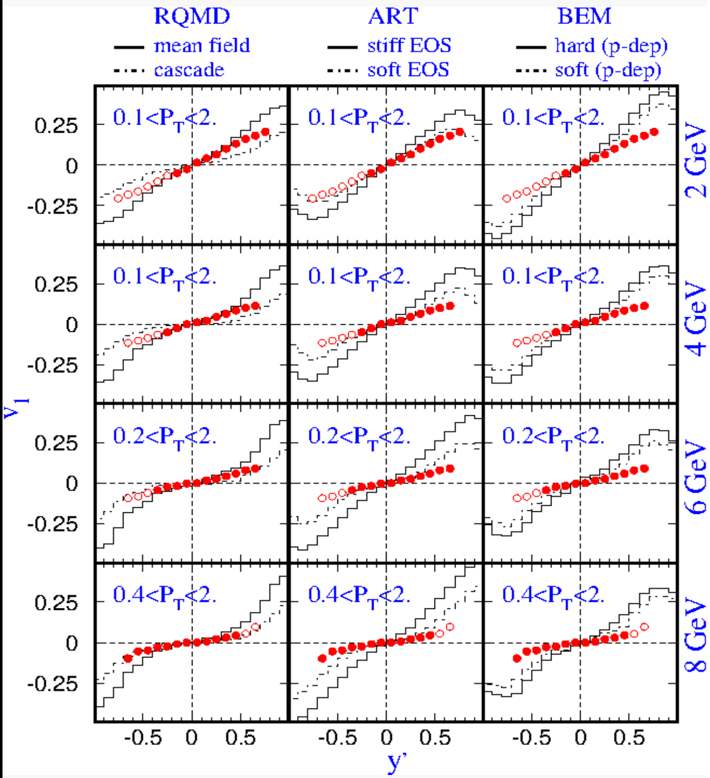


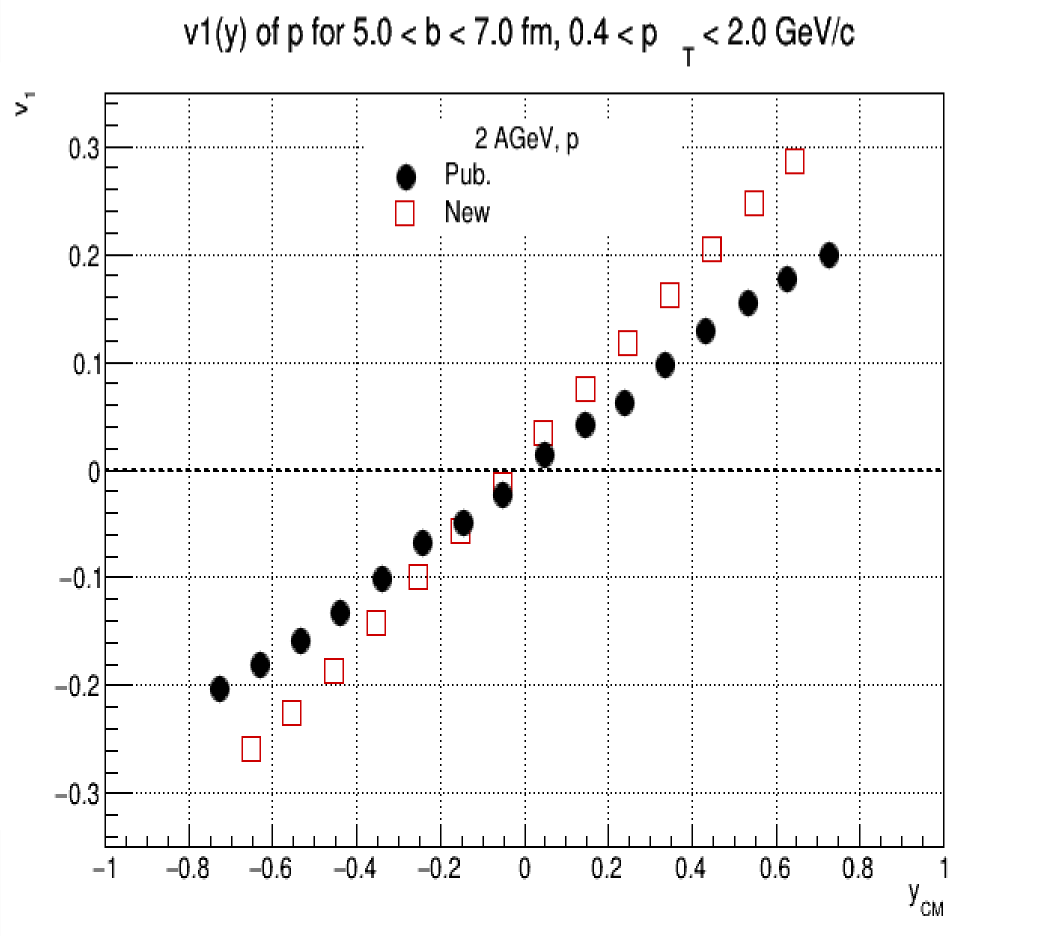
Figure shows the beam energy dependence of the slope of directed flow v_{11} for protons and deuterons with u_{t0}>0.4 cut (closed symbols) and u_{t0}>0.8 cut (open symbols). **The conclusion: slope v_{11} for protons does not change** in 0.4-1.5 AGeV or ($\sqrt{s_{NN}}$=2.1-2.5 GeV) if one use the scaled variables – I can reproduce these results by fits of the $V_1(y_0)$ data – see the previous page

Nucl. Phys. A 876 (2012) 1-60

(V_1) of protons and slope at midrapidity from E895 (AGS)

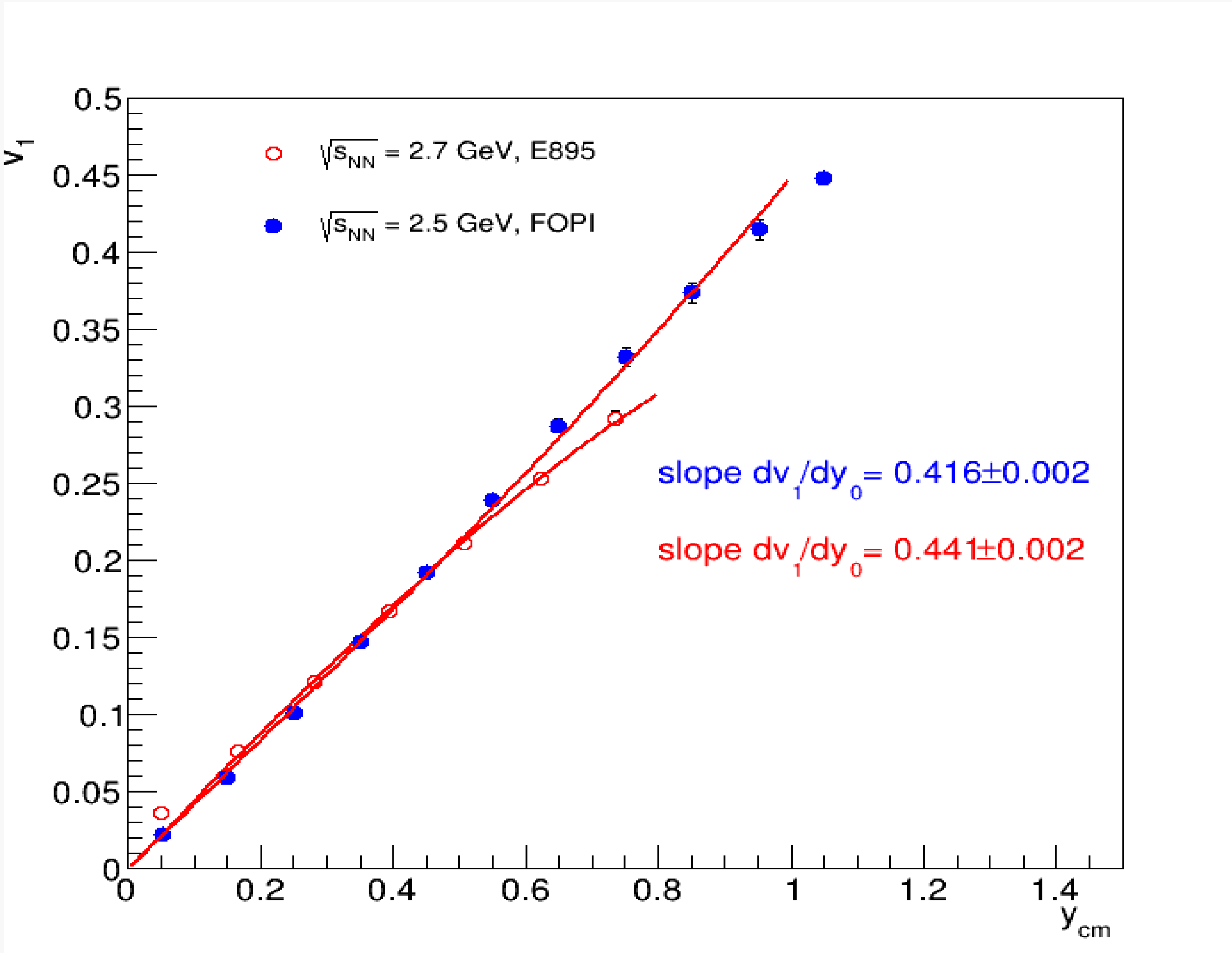


Sideward Flow in Au + Au Collisions Between 2A GeV and 8A GeV, Phys. Rev. Lett. 84, 5488 (2000)



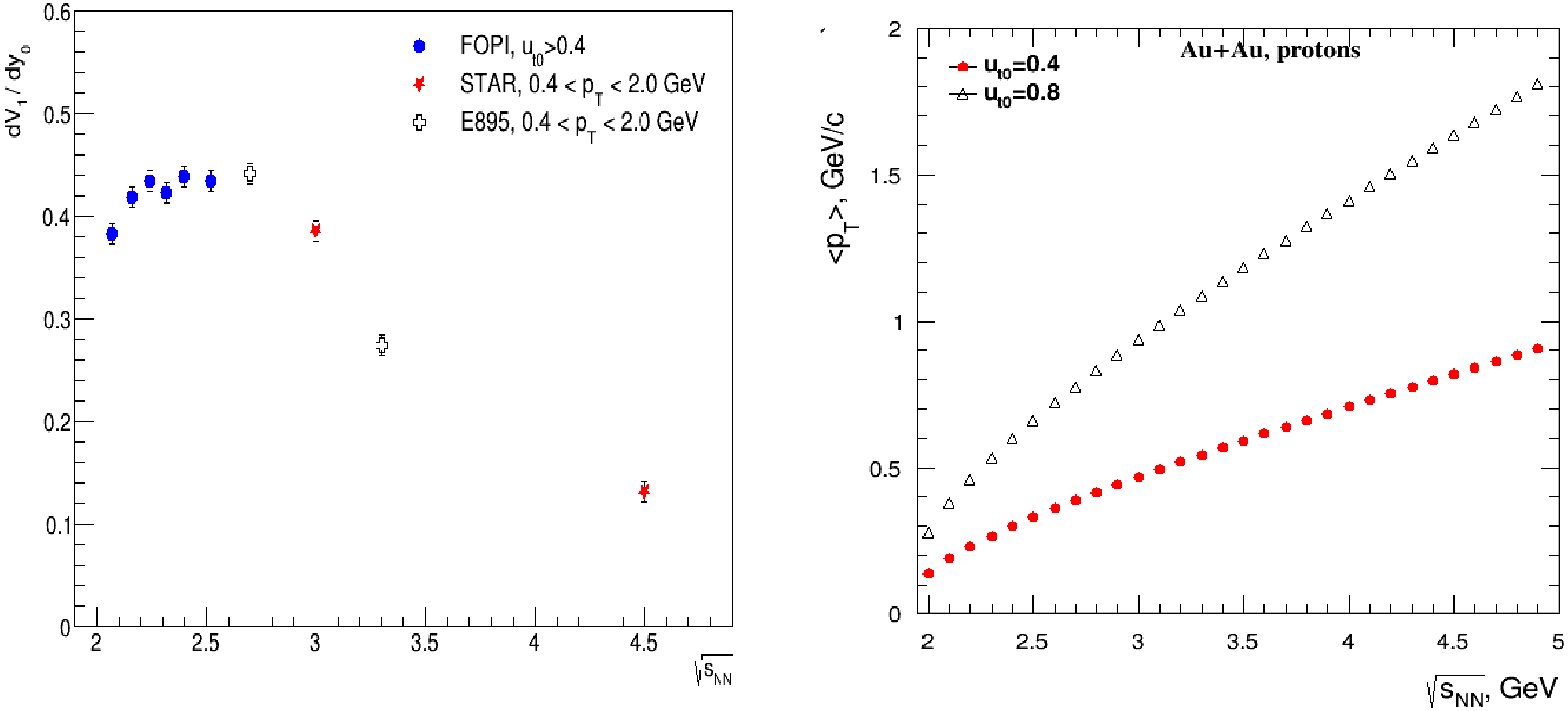
The published E895 results for V_1 of protons were obtained for $0.1 < p_T < 2.0\,\frac{GeV}{c}$ (closed symbols) – the open red boxes show the new results for $0.4 < p_T < 2.0\,\frac{GeV}{c}$

(V_1) of protons and slope at midrapidity from E895 (AGS): 2AGeV



The new E895 results for V_1 of protons which were obtained for $0.4 < p_T < 2.0 \frac{GeV}{c}$ are more close to the published FOPI data (u_{t0}>0.4 cut for 2A GeV will correspond to p_T>0.387 GeV/c cut)

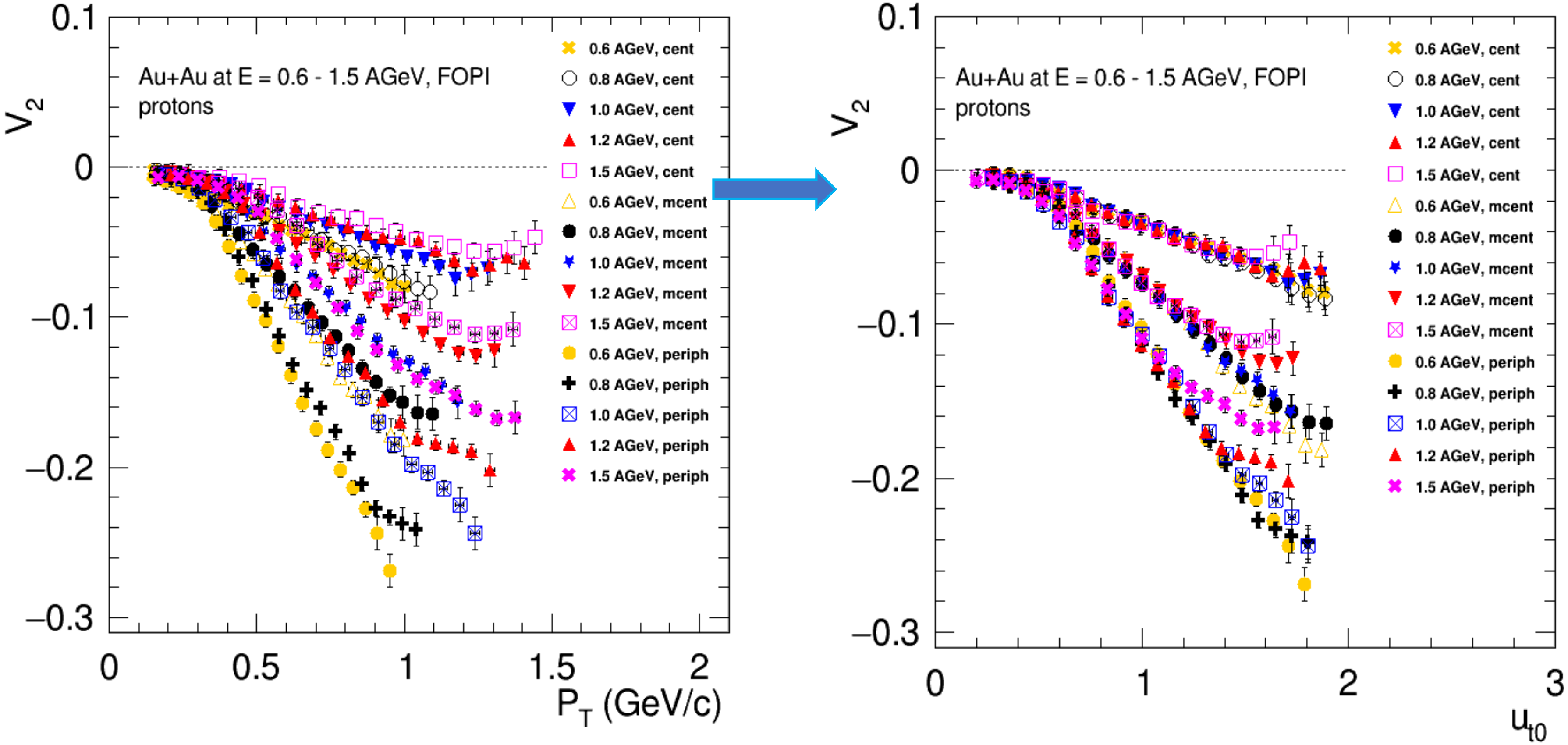
(V_1) of protons and slope at midrapidity $\sqrt{s_{NN}}$= 2.1 - 4.5 GeV



We tried to make and plot the collision energy dependence of the slope of directed flow of protons. However not all experiments are using the scaled variables $y_0 = y_{cm}/\ y_{beam}$ and u_{t0} (instead of p_T) – this creates the problem for comparison of the V_1 results from different eperiments and collision energies.

u_{t0} scaling: FOPI data (0.6-1.5 AGeV) **Protons: | y_0 | < 0.4**

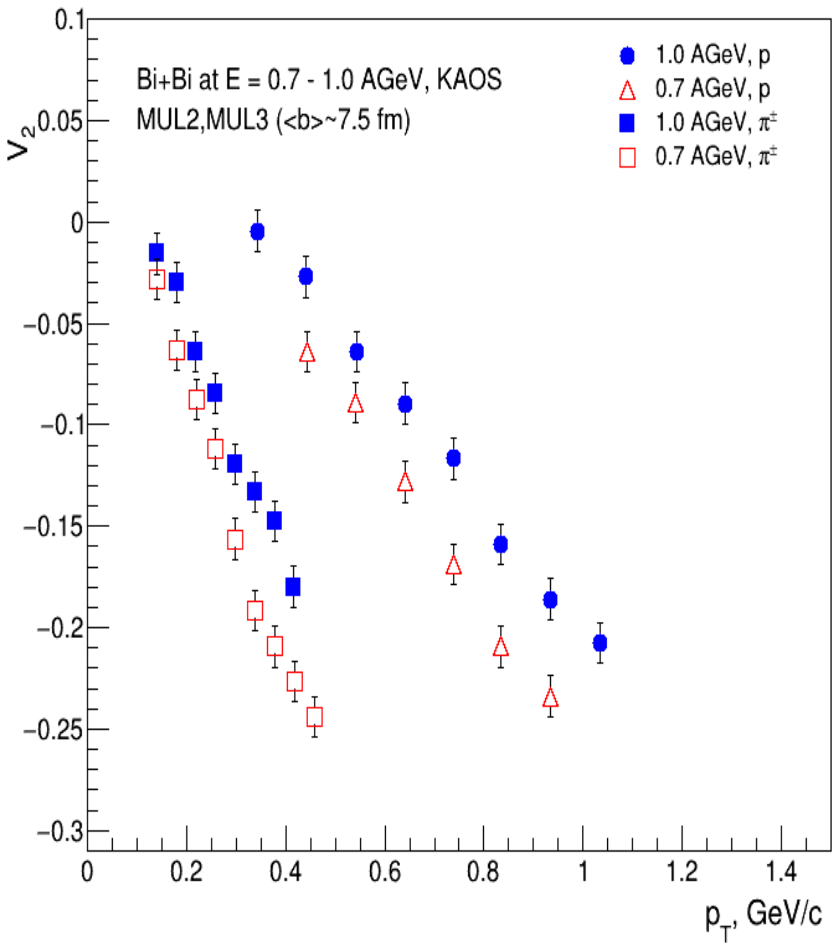
FOPI: Nucl. Phys A 876 (2012) 1-60

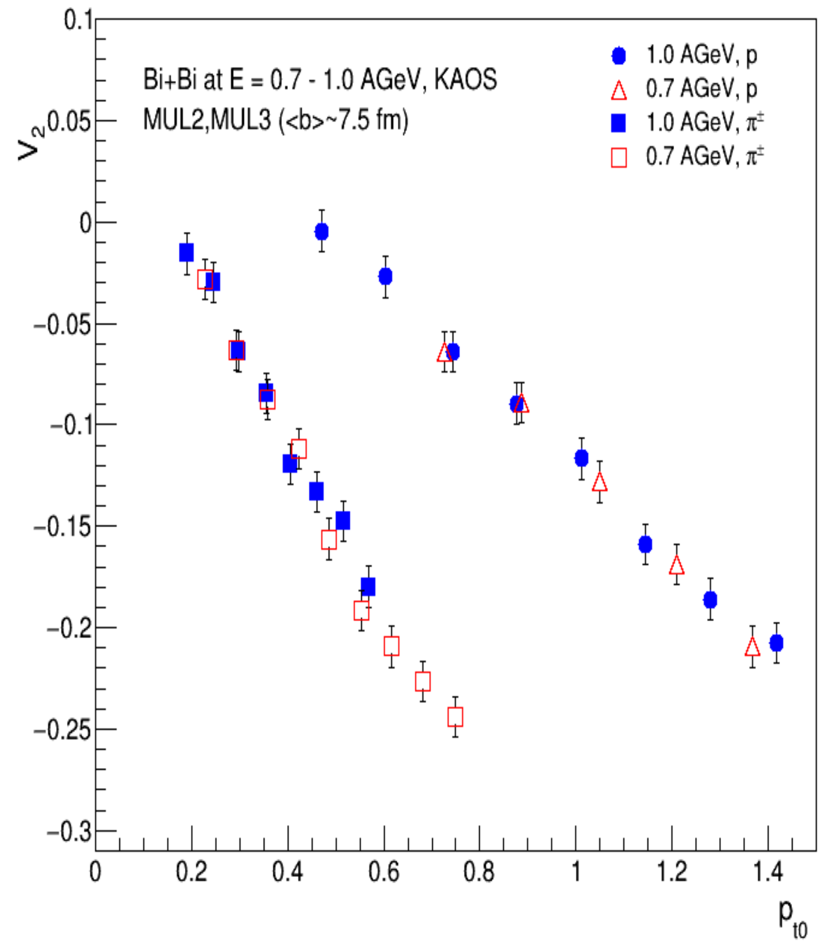


- Lets take ~300 $v_2(p_T)$ values from published data from FOPI experiment: 5 points in beam energy, 3 bins in centrality, 20 in p_T. Convert p_T to u_{t0}
- $u_{t0} = \frac{p_T}{\beta_{cm}\gamma_{cm}m_0}$ (passing time $t_{pass} = \frac{2R}{\beta_{cm}\gamma_{cm}}$ - scaling)

u_{t0} scaling: KAOS data (0.7-1.0 AGeV)

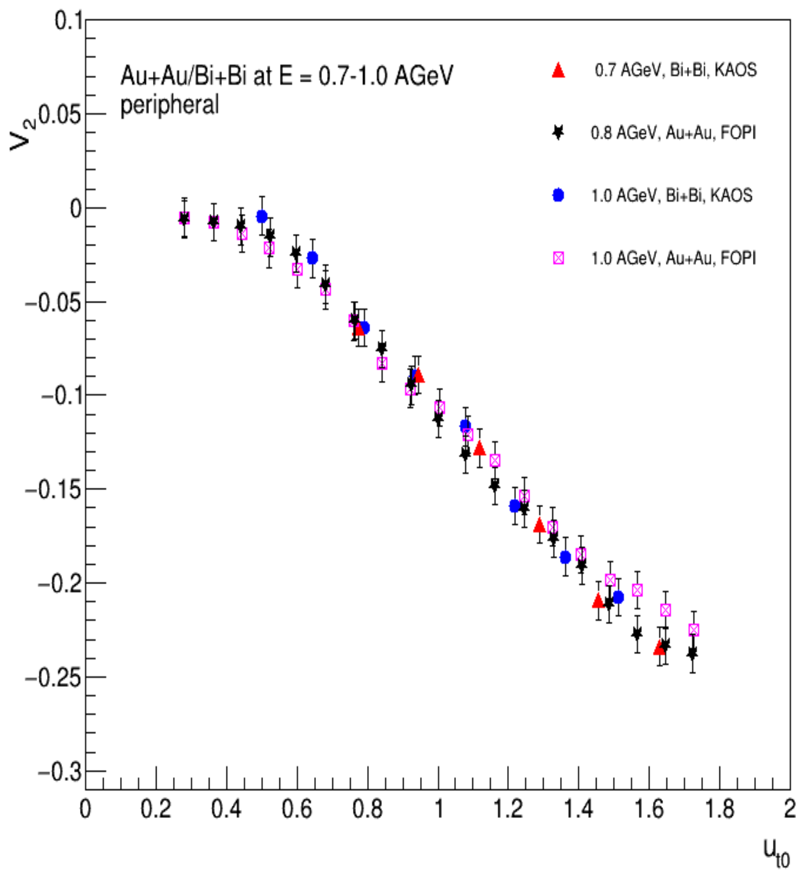
Scaling works for protons and charged pions for published KAOS data

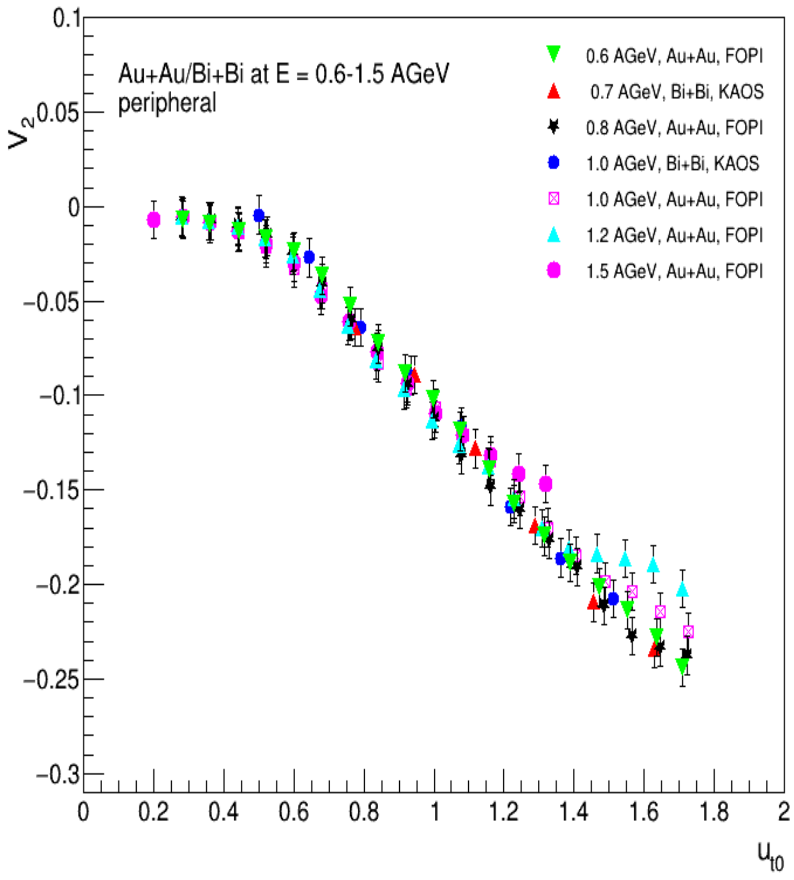




u_{t0} scaling: KAOS/FOPI data (0.6-1.5 A GeV)

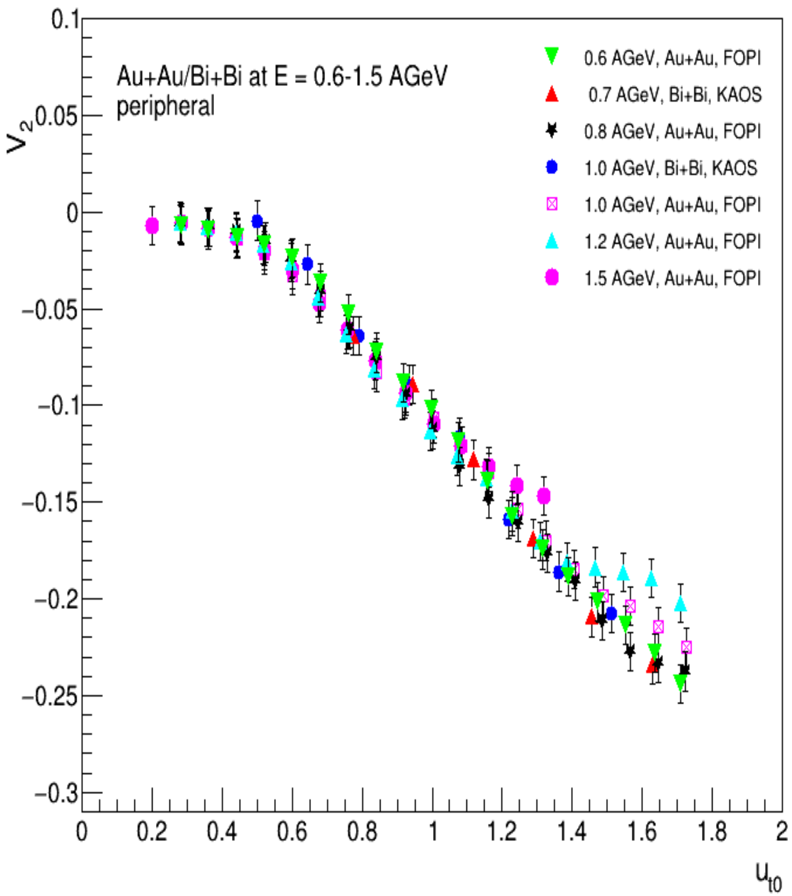
Scaling works for proton published results from KAOS and FOPI

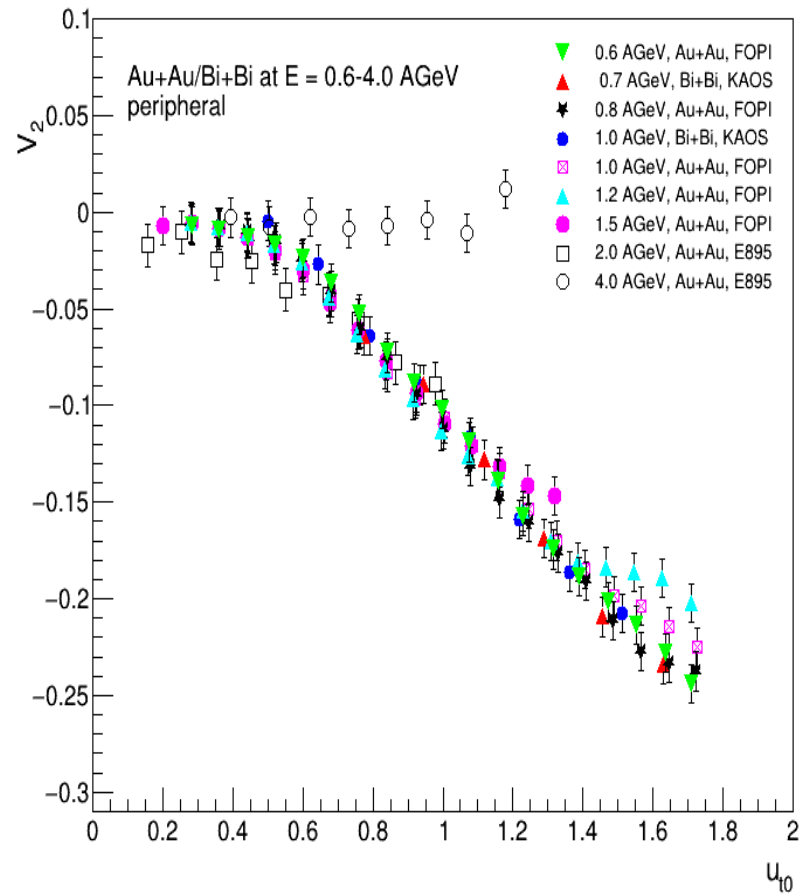




u_{t0} scaling: KAOS/FOPI/E895 data (0.6-4 A GeV)

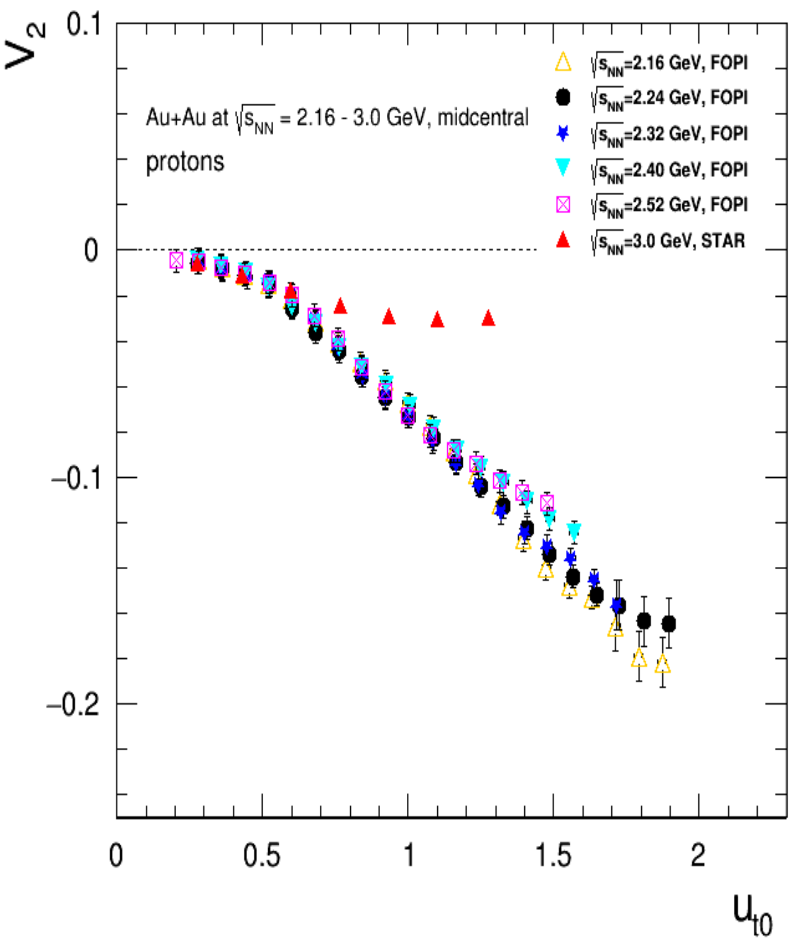
E895 published results for protons: Scaling works at 2AGeV and breaks at 4AGeV

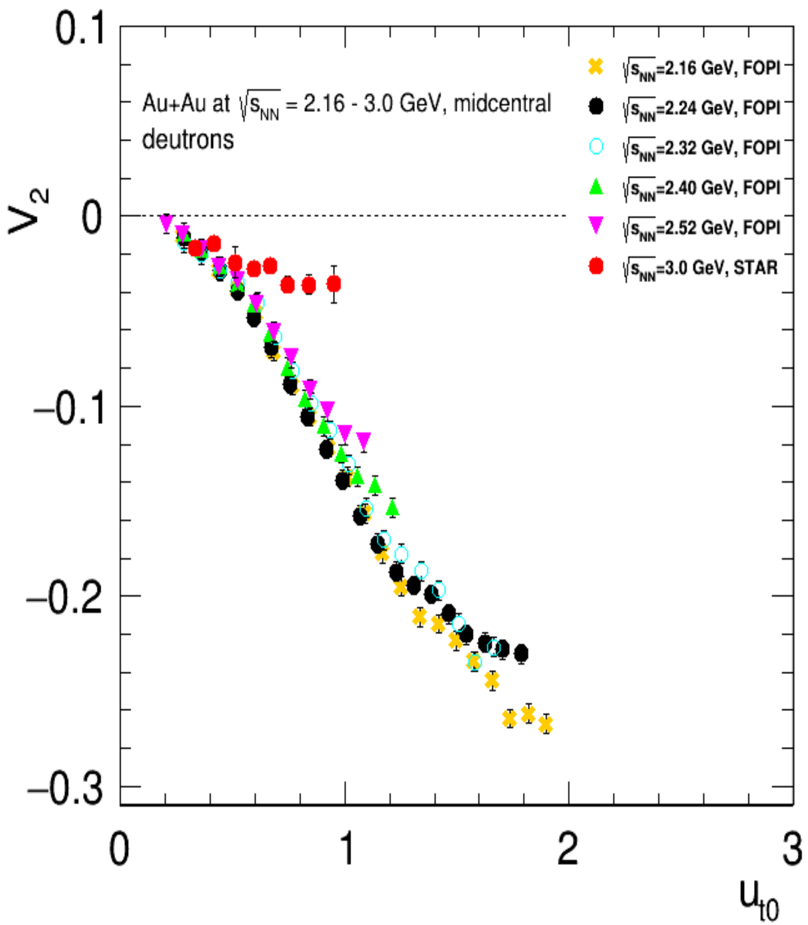




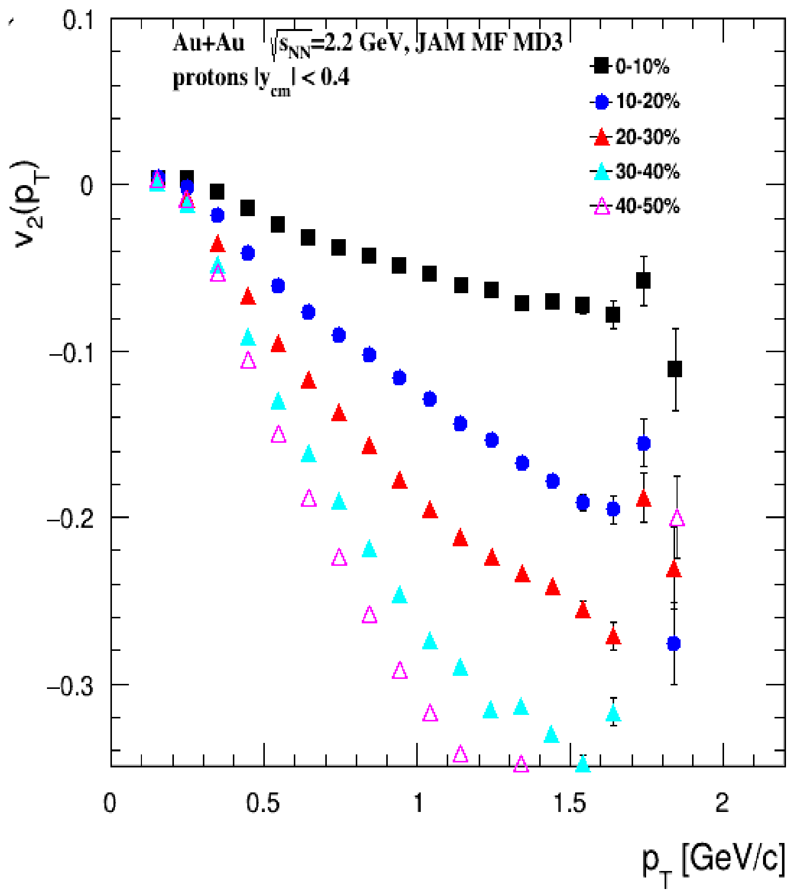
u_{t0} scaling: FOPI/STAR data

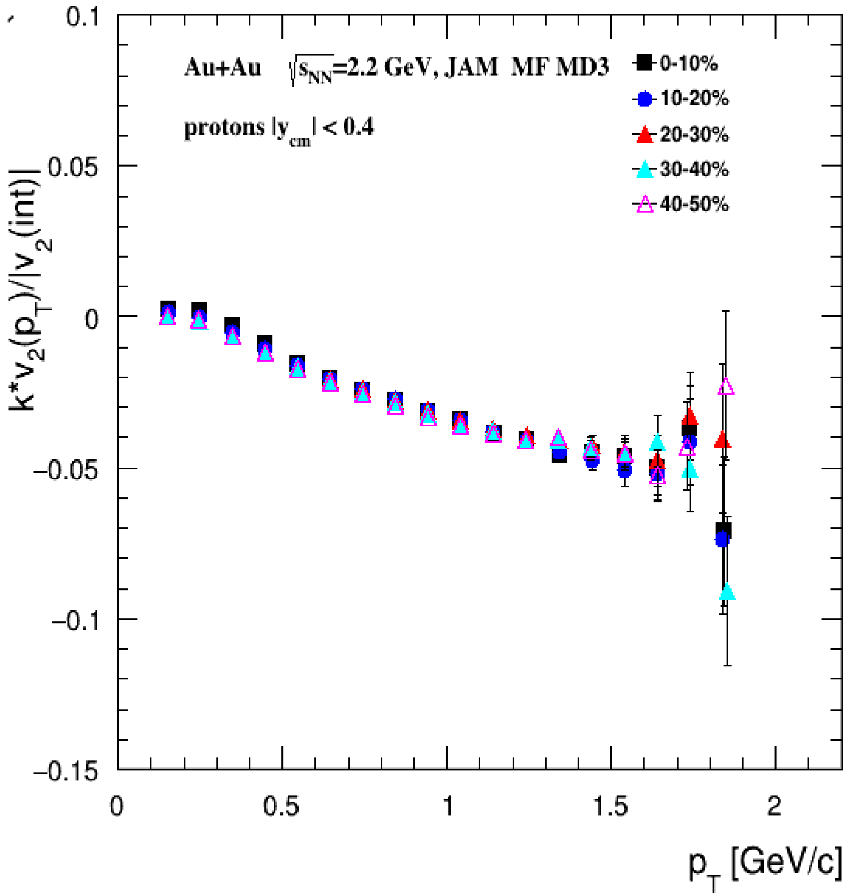
STAR published results for protons and deuterons : Scaling breaks at $\sqrt{s_{NN}}$=3GeV





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

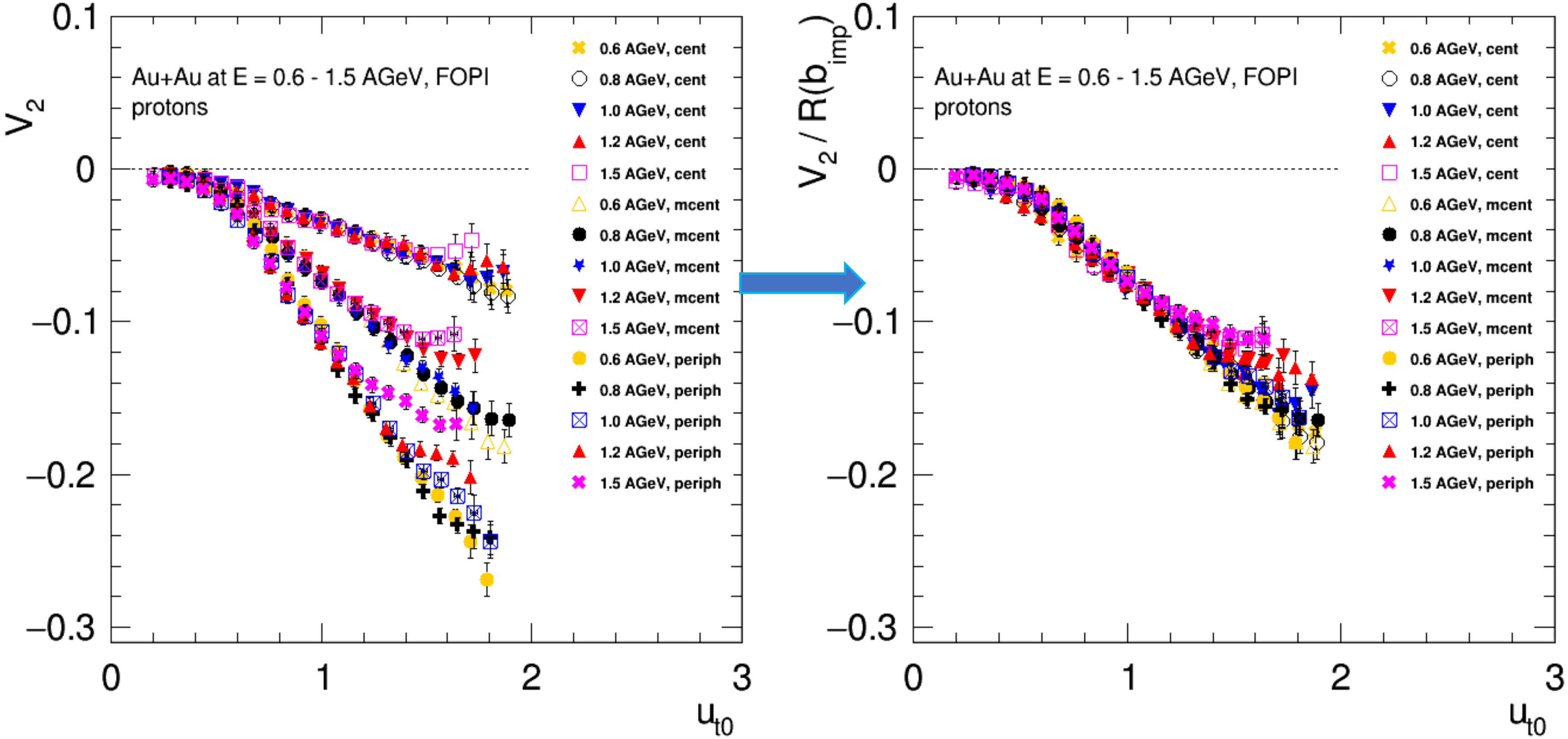




In all plots k=0.025 and v2(int) for 0.4<pT<2.0 GeV/c

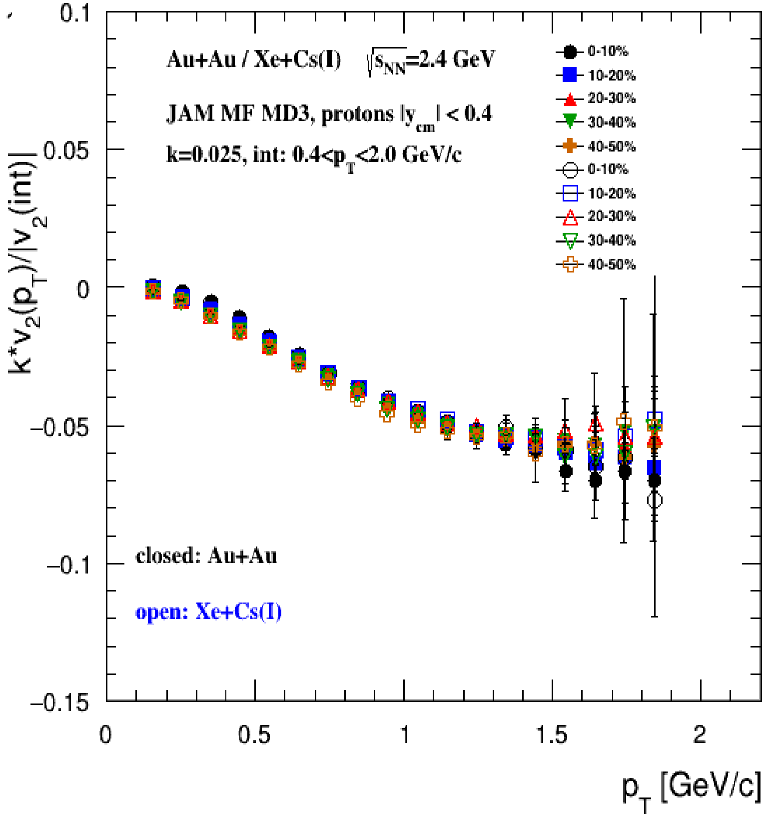
$$V_2(PID, p_T, centrality, \sqrt{s_{NN}}) = V_2(h, centrality, \sqrt{s_{NN}})^* \, V_2(PID, p_T)???$$

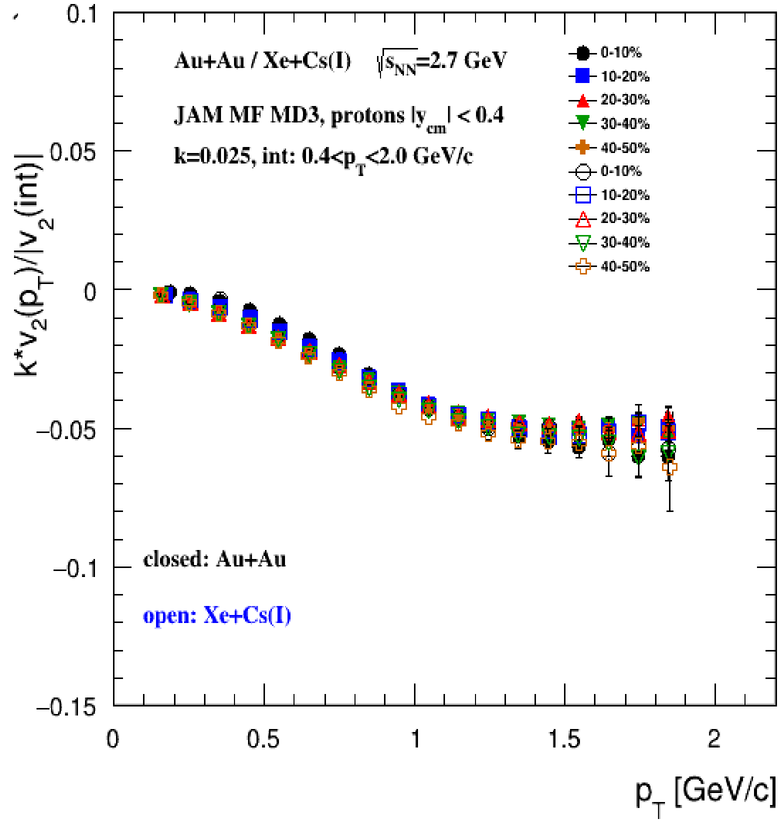
u_{t0} scaling: centrality dependence



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

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)

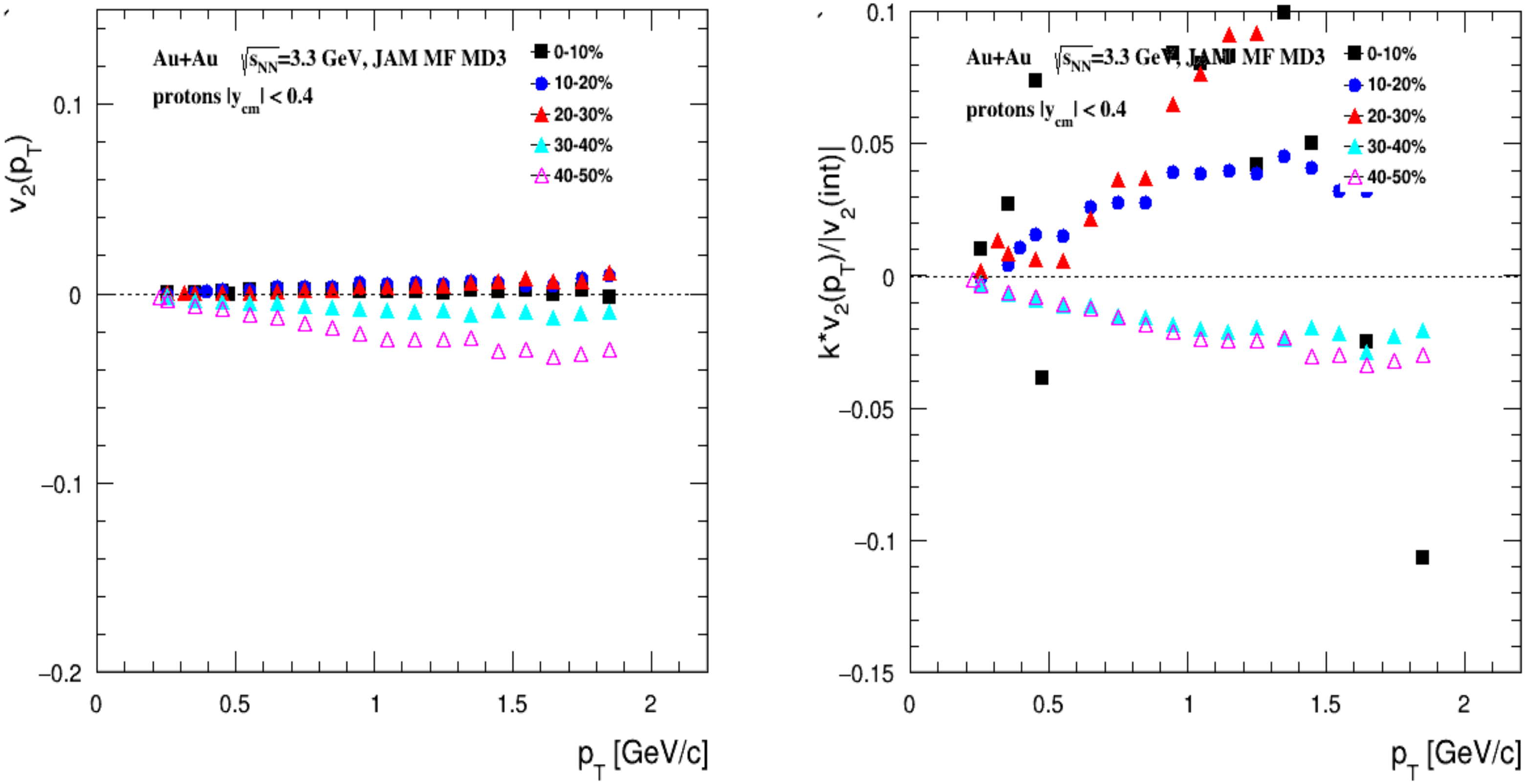




Scaling works for Au+Au and Xe+Cs(I) – general feature of the flow?

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

Scaling with integral flow of charged hadrons. Will it work at $\sqrt{s_{NN}}$ =3.3 GeV? (JAM mean field MD3)



Scaling starts to break – as the transition from out-of-plane to in-plane – strongly depends on centrality

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

STAR BES-I and BES-II Data Sets

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

Precision data to map the QCD phase diagram

$3 < \sqrt{s_{NN}} < 200$ GeV; $750 < \mu_B < 25$ MeV

Summary

“Change of collective-flow mechanism indicated by scaling analysis of transverse flow “ A. Bonasera, L.P. Csernai , **Phys. Rev. Lett. 59 (1987) 630**

The general features of the collective flow could, in principle, be expressed in terms of scale-invariant quantities. In this way the particular differences arising from the different initial conditions, masses, energies, etc. , can be separated from the general fluid-dynamical features

“Collective flow in heavy-ion collisions”, W. Reisdorf, H.G. Ritter Ann.Rev. Nucl.Part.Sci. 47 (1997) 663-709 :

There is interest in using observables that are both coalescence and scale-invariant. …The evolution in non-viscous hydrodynamics does not depend on the size of the system nor on the incident energy, if distances are rescaled in terms of a typical size parameter, such as the nuclear radius. Momenta and energies are rescaled in terms of the beam velocities, momenta or energies.

The proposal to look for scaling relations and use them – is very – very old !!!!

Summary

BACKUP

STAR ☆

$\sqrt{s_{NN}}$ (GeV)	Beam Energy (GeV/nucleon)	Collider or Fixed Target	$y_{center\ of\ mass}$	μ_B (MeV)	Run Time (days)	No. Events Collected (Request)	Date Collected
200	100	C	0	25	2.0	138 M (140 M)	Run-19
27	13.5	C	0	156	24	555 M (700 M)	Run-18
19.6	9.8	C	0	206	36	582 M (400 M)	Run-19
17.3	8.65	C	0	230	14	256 M (250 M)	Run-21
14.6	7.3	C	0	262	60	324 M (310 M)	Run-19
13.7	100	FXT	2.69	276	0.5	52 M (50 M)	Run-21
11.5	5.75	C	0	316	54	235 M (230 M)	Run-20
11.5	70	FXT	2.51	316	0.5	50 M (50 M)	Run-21
9.2	4.59	C	0	372	102	162 M (160 M)	Run-20+20b
9.2	44.5	FXT	2.28	372	0.5	50 M (50 M)	Run-21
7.7	3.85	C	0	420	90	100 M (100 M)	Run-21
7.7	31.2	FXT	2.10	420	0.5+1.0+ scattered	50 M + 112 M + 100 M (100 M)	Run-19+20+21
7.2	26.5	FXT	2.02	443	2+Parasitic with CEC	155 M + 317 M	Run-18+20
6.2	19.5	FXT	1.87	487	1.4	118 M (100 M)	Run-20
5.2	13.5	FXT	1.68	541	1.0	103 M (100 M)	Run-20
4.5	9.8	FXT	1.52	589	0.9	108 M (100 M)	Run-20
3.9	7.3	FXT	1.37	633	1.1	117 M (100 M)	Run-20
3.5	5.75	FXT	1.25	666	0.9	116 M (100 M)	Run-20
3.2	4.59	FXT	1.13	699	2.0	200 M (200 M)	Run-19
3.0	3.85	FXT	1.05	721	4.6	259 M -> 2B(100 M -> 2B)	Run-18+21

5