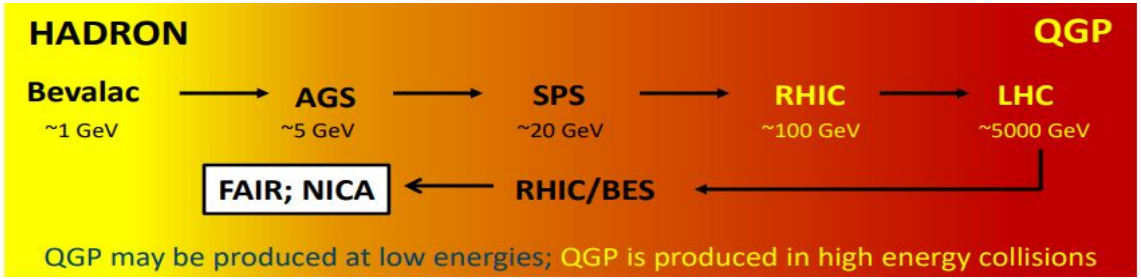
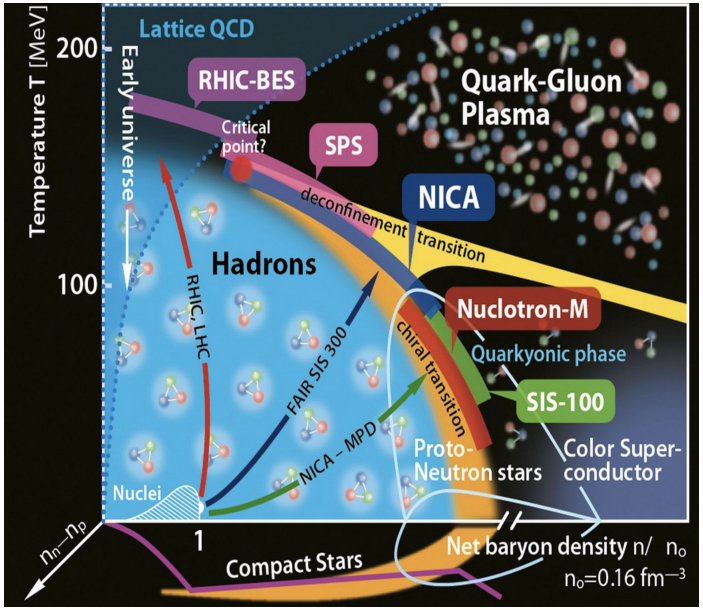
Исследование эллиптического потока адронов в столкновениях тяжелых ионов в диапазоне энергий ускорительного комплекса NICA

Петр Парфенов (pparfenov@jinr.ru)

Общелабораторный семинар ЛФВЭ, 10 апреля, 2026

Relativistic heavy-ion collisions



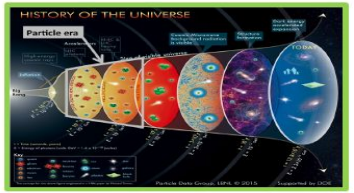


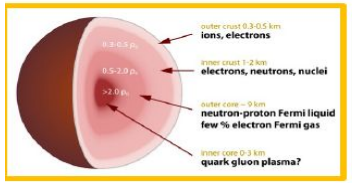
1970s-2000s – nuclear equation of state (EoS), search for the quark-gluon plasma (QGP)
2005s – QGP formation was observed at RHIC and it behaves as almost perfect liquid
2005-2010s – LQCD predicts crossover phase transition at top RHIC and LHC (high T, $\mu_B \approx 0$)

Since 2010s – Beam energy scans to study QCD phase diagram: search for the 1st order phase transition and CEP at Intermediate T, high μ_B

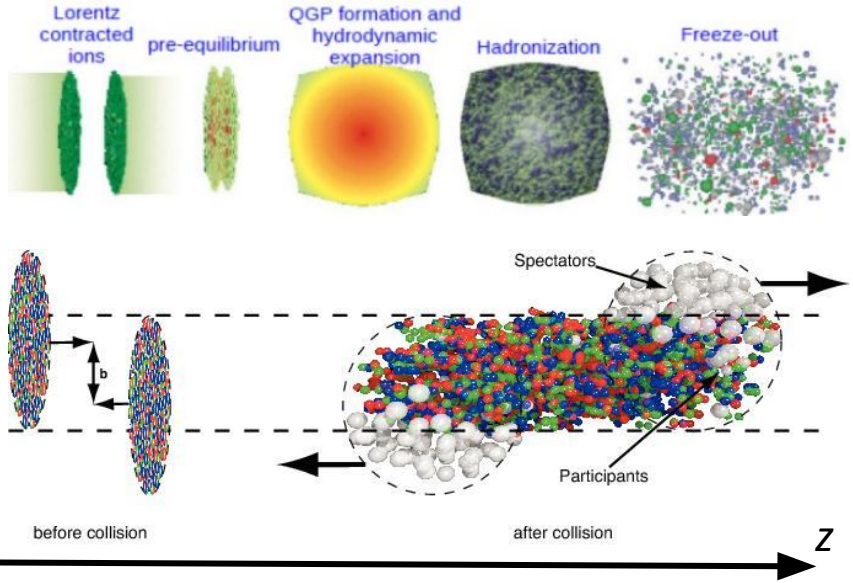
Relativistic heavy-ion collisions allows us to study QCD phase diagram

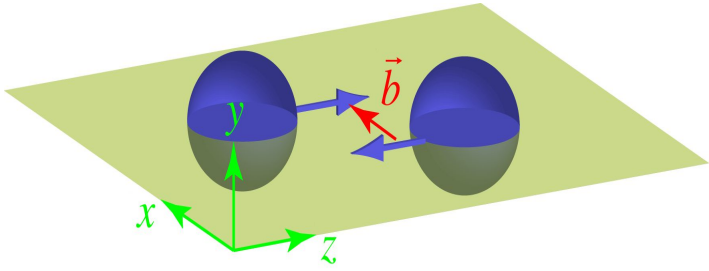
- **High beam energies ($\sqrt{s_{NN}}$>100 GeV):**
  - High T, $\mu_B \approx 0$
  - Evolution of the early Universe
- **Low beam energies (2.4<$\sqrt{s_{NN}}$<11 GeV):**
  - Intermediate T, high μ_B
  - Inner structure of the compact stars, neutron star mergers

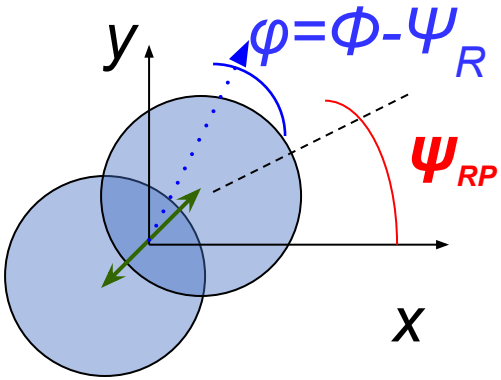




Geometry of heavy-ion collision

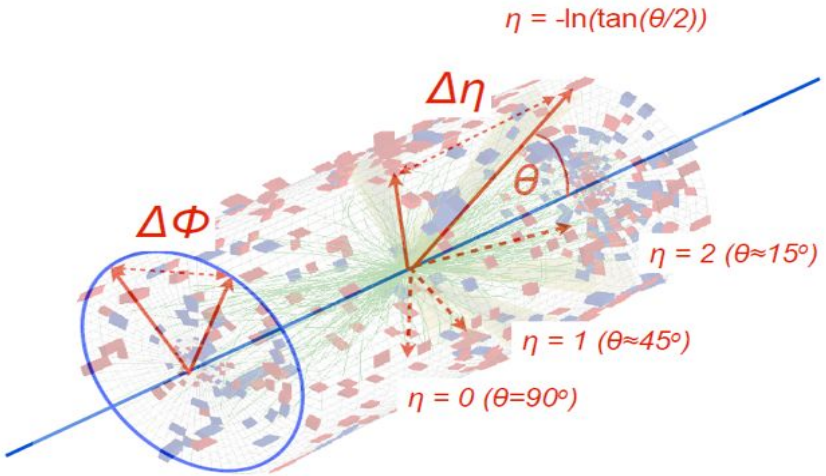






- **Impact parameter:** connects centers of colliding nuclei
  - **Central collisions (b=0):** many produced particles (participants), few spectator nucleons
  - **Peripheral collisions (b≤2R):** few produced particles (participants), many spectator nucleons
- **Reaction plane:** spanned by the beam direction (***z***) and the impact parameter (*b*)

HIC: Angular and kinematical variables



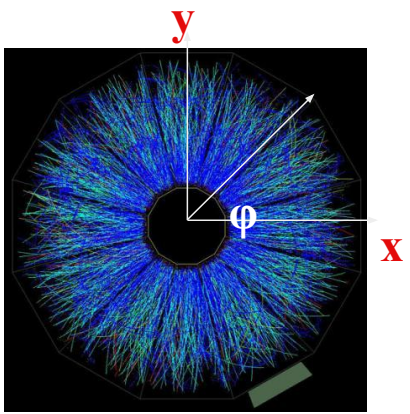
- **φ - azimuthal angle**
- **θ - polar angle**
- **η - pseudo-rapidity**

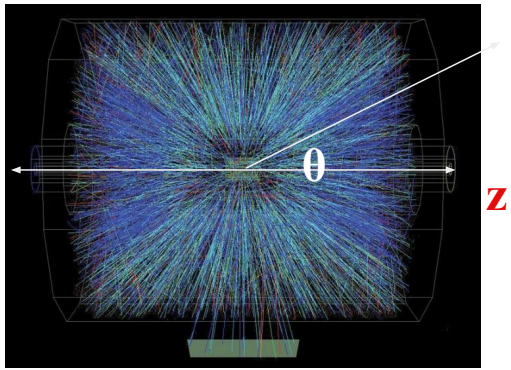
$$\eta = -\ln\left(\tan\left(\frac{\theta}{2}\right)\right)$$

- **y – rapidity**

$$y = \frac{1}{2}\ln\left(\frac{E + p_z}{E - p_z}\right)$$

- **p_T -transverse momentum**



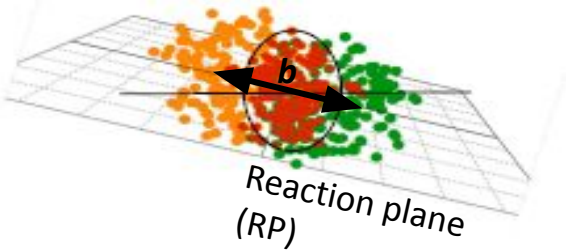


$$p_T = \sqrt{p_x^2 + p_y^2}$$

$$m_T = \sqrt{m^2 + p_T^2}$$

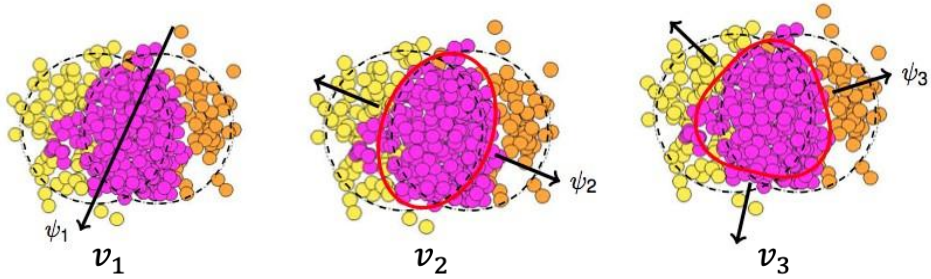
Anisotropic collective flow

Anisotropy of the initial spacial geometry



Multiple scattering in the overlap region

Momentum anisotropy of the final-state particles



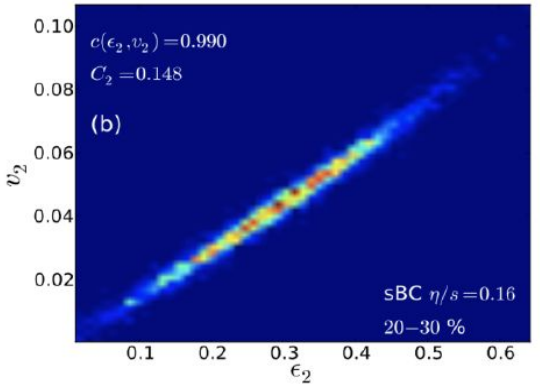
$$\epsilon_n = \sqrt{\frac{\langle r^n \cos n\phi \rangle + \langle r^n \sin n\phi \rangle}{\langle r^n \rangle}}$$

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

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

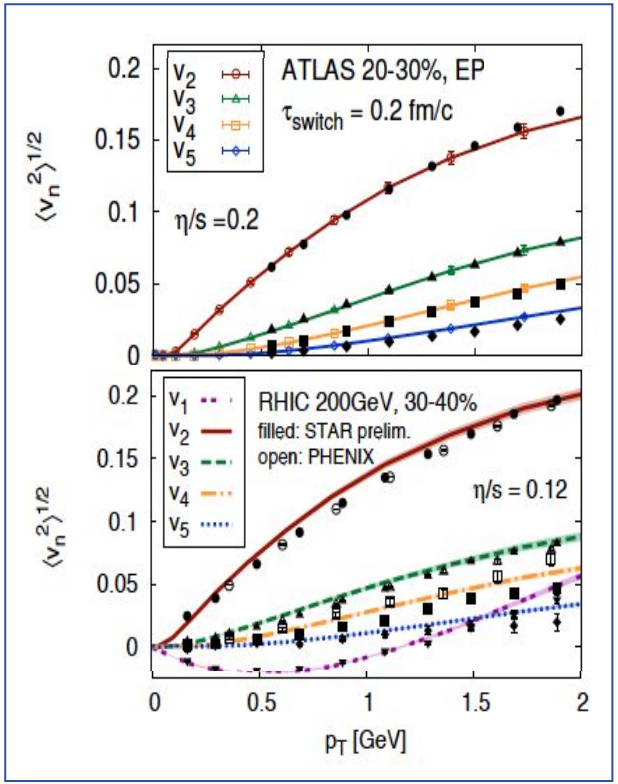
v_1 - directed flow, v_2 - elliptic flow, v_3 -triangular flow

Initial eccentricity (and its attendant fluctuations) ε_n drives momentum anisotropy v_n with specific viscous modulation

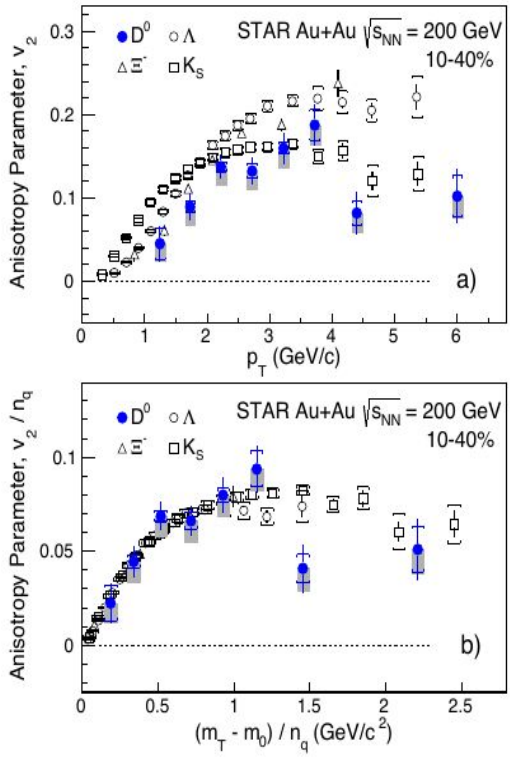


Anisotropic flow at LHC/top RHIC

Gale, Jeon, et al., Phys. Rev. Lett. 110, 012302



STAR PRL118 (2017) 212301



$v_n(p_T, \mathbf{Centrality})$ - sensitive to the early stages of the collision

Important constrain for transport properties and EOS (η/s, ζ/s, etc.)

v_n of identified hadrons:

- **Mass ordering at p_T<2 GeV/c** (hydrodynamic flow, hadron rescattering)
- **Baryon/meson grouping at p_T>2 GeV/c** (recombination/coalescence) Number of constituent quark (NCQ) scaling

Non-flow correlations and v_2 fluctuations

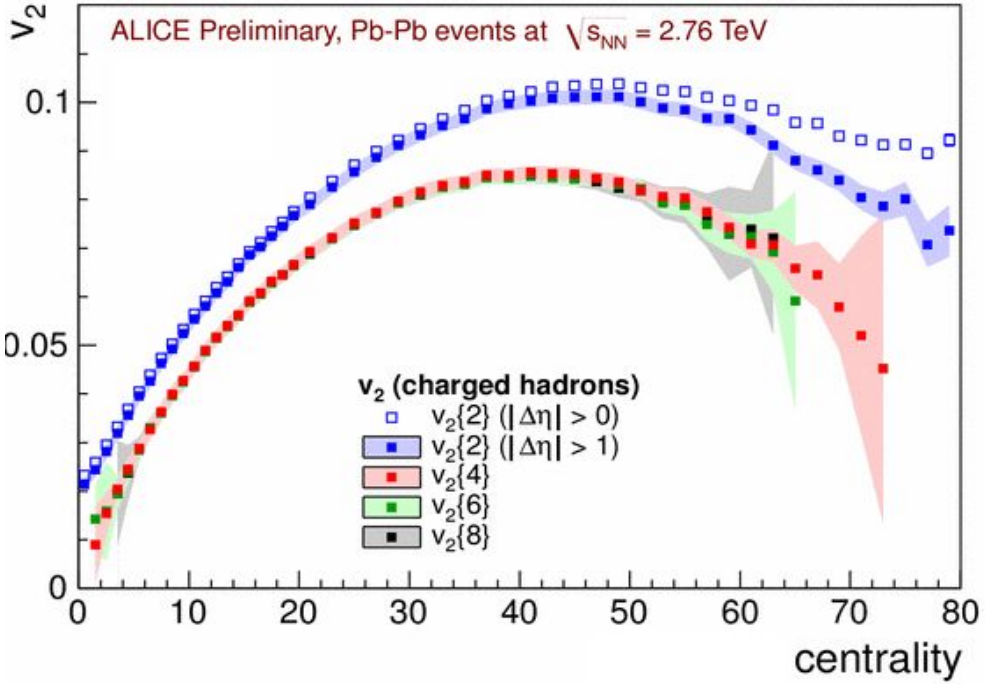
There are correlations between particles that are not related to the reaction plane. These correlations are called "non-flow"

Among the sources of non-flow correlations are:

- Conservation of total (transverse) momentum during collisions;
- Resonance decays due to weak interactions;
- Short-range correlations (femtoscopy, decay of nuclear fragments)

Detector effects can also introduce correlated bias into the flow measurements:

- Splitting the trajectory of one particle as a result of reconstruction
- Merging the trajectories of two particles as a result of reconstruction
- Signals from the passage of the same particle in the adjacent modules of the segmented detectors



As a rule, “non-flow” correlations have a significant effect only on particles with close momenta; they can also be suppressed by increasing the rapidity interval between particles.

Sensitivity of $v_2\{QC\}$ to flow fluctuations and non-flow

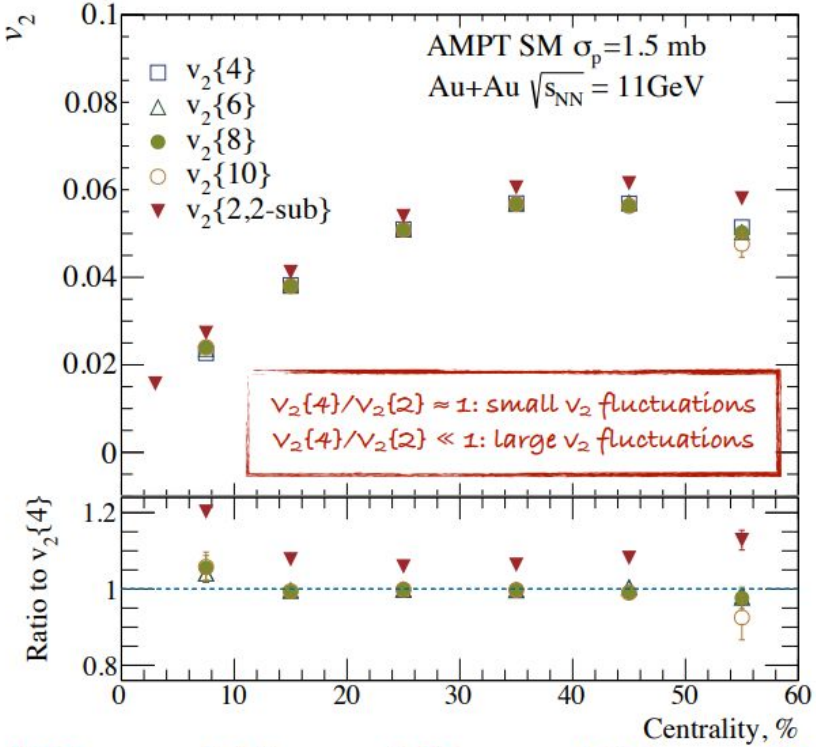
- Non-flow contribution for k-particle cumulants: $\delta_k \sim 1/M^{k-1}$
- Elliptic flow fluctuations: $\sigma^2_{v_2} = \langle v_2^2 \rangle - \langle v_2 \rangle^2$
- Assuming $\sigma_{v_2} << \langle v_2 \rangle$, fluctuations enhance $v_2\{2\}$ and suppress $v_2\{2k,k>1\}$ compared to $\langle v_2 \rangle$

$$v_2\{2\} \approx \langle v_2 \rangle + \frac{1}{2}\frac{\sigma^2_{v_2}}{\langle v_2 \rangle}$$

$$v_2\{4\} \approx \langle v_2 \rangle - \frac{1}{2}\frac{\sigma^2_{v_2}}{\langle v_2 \rangle}$$

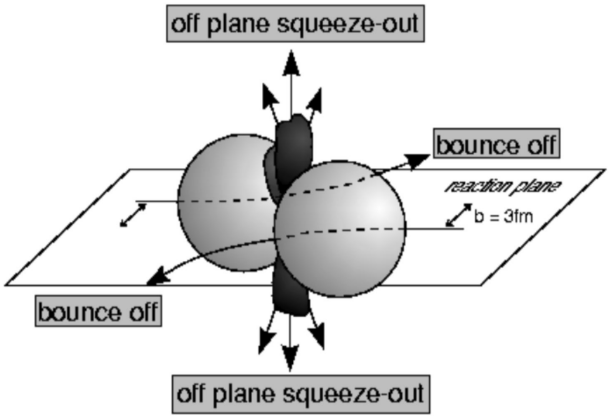
- Assuming a Gaussian form of fluctuations

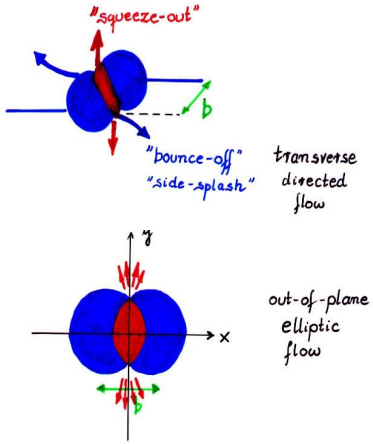
$$v_2\{4\} \approx v_2\{6\} \approx v_2\{8\} \approx v_2\{10\}$$



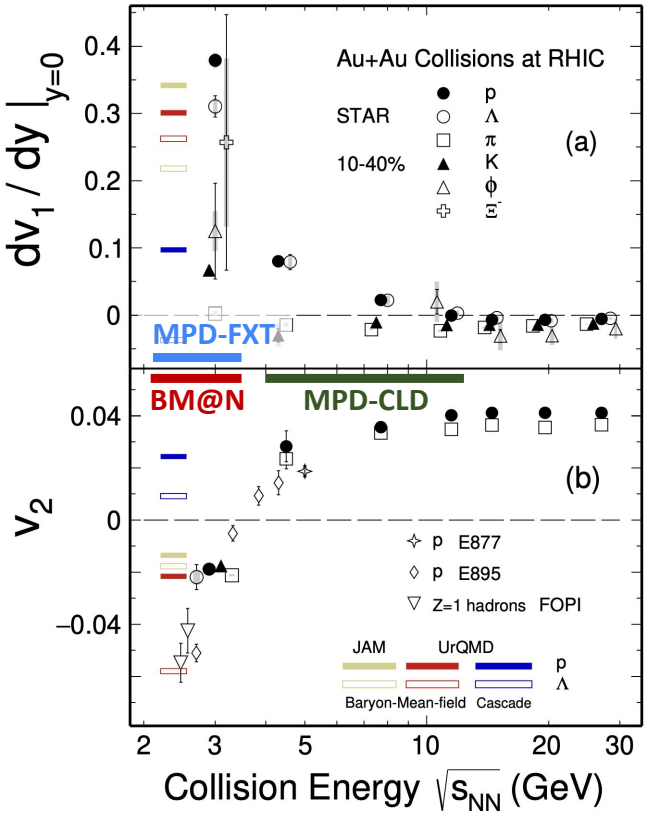
$$v_2\{2\} > v_2\{4\} \approx v_2\{6\} \approx v_2\{8\} \approx v_2\{10\}$$

Anisotropic flow at Nuclotron-NICA energies





STAR, Phys.Lett.B 827 (2022) 137003



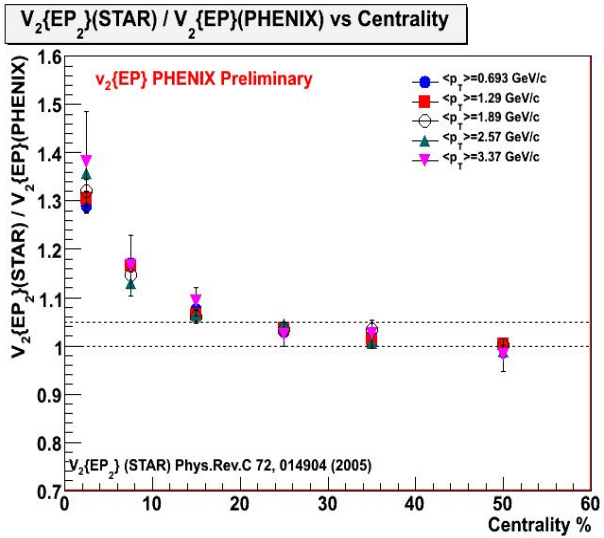
Strong energy dependence of dv_1/dy and v_2 at $\sqrt{s_{NN}}$=2-11 GeV

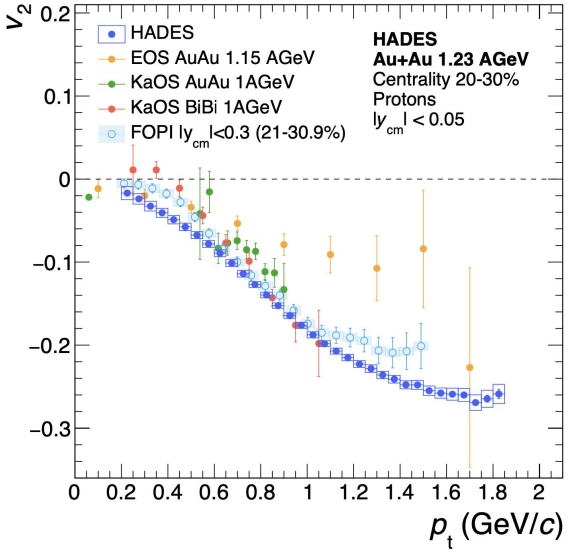
Anisotropic flow at Nuclotron-NICA energies is a delicate balance between:

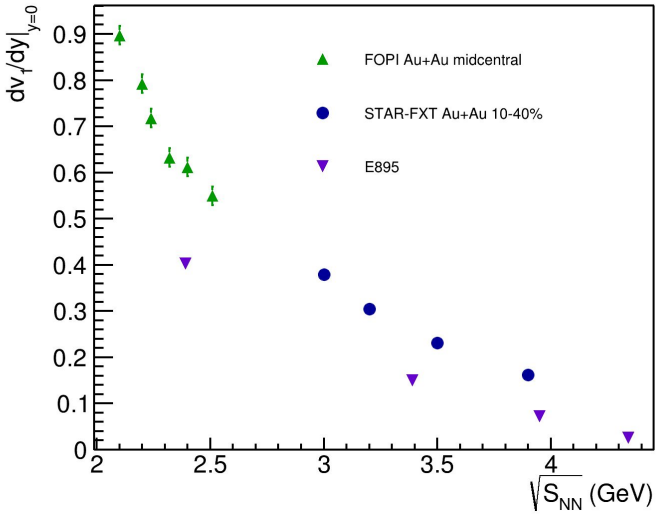
I. The ability of pressure developed early in the reaction zone ($t_{exp} = R/c_s$)

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

Discrepancy between experimental results







- **Different experiments are susceptible to detector biases and parasitic effects differently**
- **There were no infrastructure (nor cpu power) to perform full realistic simulation of reconstructed data**
- **It is important to use the same methods for v_n measurements in both models and experimental data**

MPD experiment at NICA

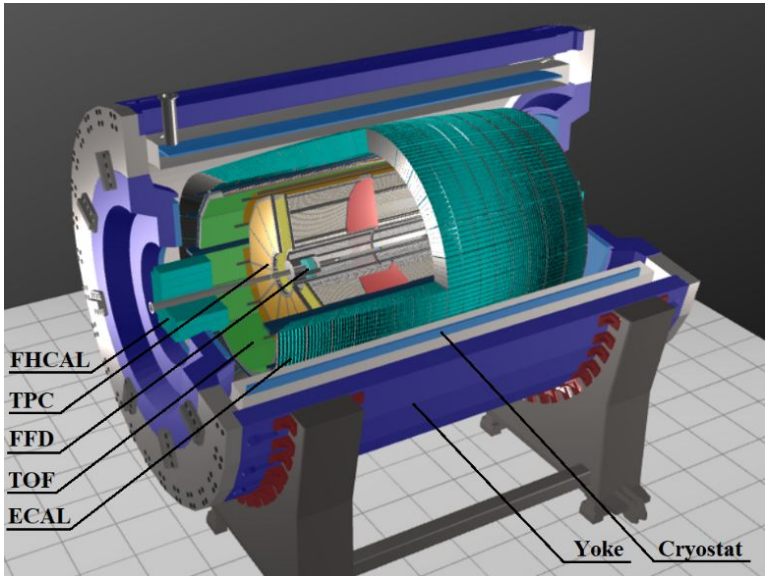
Main subsystems at Stage-I:

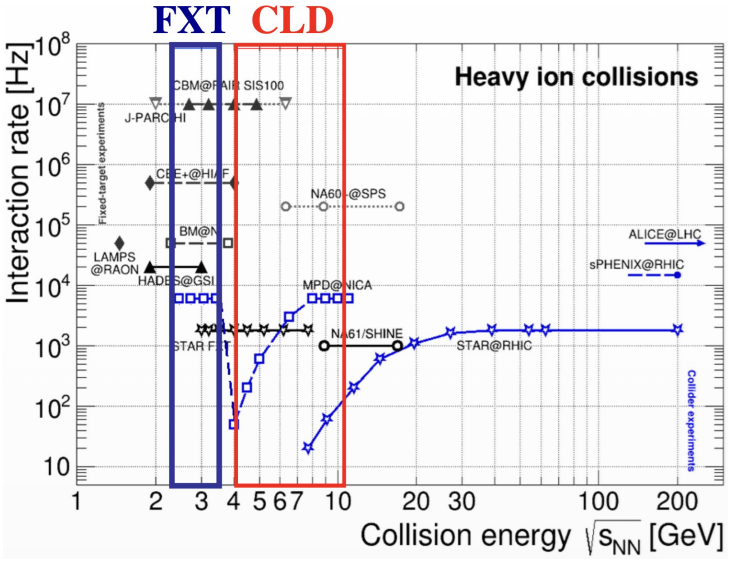
TPC ($|\eta| \leq 1.6$): charged particle tracking + momentum reconstruction + dE/dx identification

TOF ($|\eta| \leq 1.4$): charged particle identification

ECal ($2.9 < |\eta| < 1.4$): energy and PID for $\gamma/e^{\pm}$

FHCal ($2 < |\eta| < 5$) and **FFD** ($2.9 < |\eta| < 3.3$): event triggering + event geometry





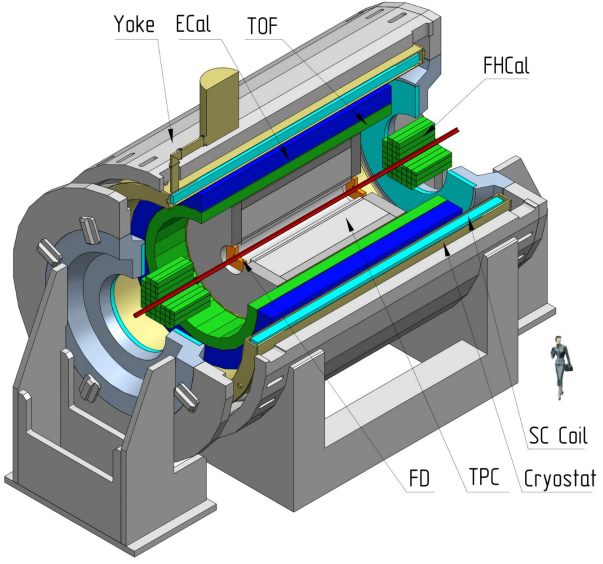
Expected beams at the first year(s) of operation (Stage-I):

- MPD-CLD: Xe/Bi+Xe/Bi at $\sqrt{s_{NN}} \sim 7$ GeV
- MPD-FXT: Xe/Bi +W at $\sqrt{s_{NN}} \sim 3$ GeV

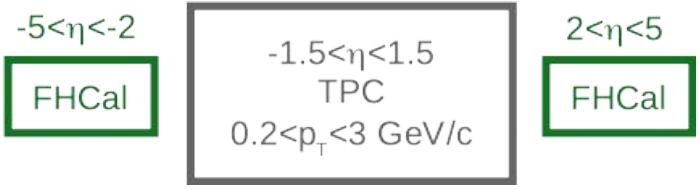
Beam energy overlap: HADES, STAR BES, NA61/SHINE and future CBM

Realistic reconstructed data in the MPD experiment

UrQMD → GEANT4 → Reconstruction → Flow analysis



Both the MPD infrastructure and the capabilities of the computing resources allow for the realistic data acquisition using GEANT4 and reconstruction with statistics comparable to those of the experimental data from the existing experiments



Цели и задачи

Разработка и апробация совокупности методов измерения эллиптического потока адронов в столкновениях тяжелых ионов в диапазоне энергий ускорительного комплекса NICA

Для достижения данной цели были решены следующие задачи:

1. Разработать библиотеки и программные пакеты с методами для определения центральности и измерения v_2.
2. Используя разработанные методы, провести системный сравнительный анализ современных модельных данных с существующими экспериментальными результатами.
3. Проверить свойства масштабирования, флуктуации v_2 и корреляцию v_2 с $[p_T]$ на моделях с реалистичными значениями v_2.
4. Проверить разработанные методы, используя экспериментальные данные STAR.
5. Провести исследование эффективности измерения v_n с использованием реалистичных реконструированных данных MPD со статистикой, сопоставимой по размеру с данными в действующих современных экспериментах.

Список публикаций

1) Relating Charged Particle Multiplicity to Impact Parameter in Heavy-Ion Collisions at NICA Energies, Petr Parfenov, Taranenko A., Idrisov D., Particles 4 (2021) 2, 275-287
2) Centrality Determination in Heavy-ion Collisions with MPD Detector at NICA, Petr Parfenov, et. al., Acta Physica Polonica B Proceedings Supplement 14 (2021) 3, 503-506
3) Model Study of the Energy Dependence of Anisotropic Flow in Heavy-Ion Collisions at $\sqrt{s_{NN}}$ = 2–4.5 GeV, Petr Parfenov, Particles 5 (2022) 4, 561-579
4) Elliptic Flow and Its Fluctuations from Transport Models for Au+Au Collisions at $\sqrt{s_{NN}}$ = 7.7 and 11.5 GeV, Petr Parfenov, Luong V.B., Particles 6 (2022) 1, 17-29
5) Model study of the energy dependence of the correlation between anisotropic flow and the mean transverse momentum in Au+Au collisions, Petr Parfenov, Magdy N. et. al., Phys.Rev.C 105 (2022) 4, 044901
6) Study of the Correlation Between Mean Transverse Momentum and Elliptic Flow in Au + Au Collisions at NICA Energies, Petr Parfenov, Idrisov D., Phys.Atom.Nucl. 86 (2023) 5, 908-912
7) Elliptic (v_2) and triangular (v_3) anisotropic flow of identified hadrons from the STAR Beam Energy Scan program, Petr Parfenov, J.Phys.Conf.Ser. 1690 (2020) 1, 012128
8) Anisotropic Flow Measurements of Identified Hadrons with MPD Detector at NICA, Petr Parfenov, Particles 4 (2021) 2, 146-158
9) Anisotropic Flow Measurements of Identified Hadrons with Fixed-Target Mode of MPD Detector at NICA, Petr Parfenov, Taranenko A., Mamaev M., Phys.Part.Nucl. 55 (2024) 4, 853-858
10) Feasibility Study of Anisotropic Flow Measurements of Identified Charged Hadrons in the MPD Experiment with a Fixed Target, Petr Parfenov, Taranenko A., Mamaev M., Phys.Part.Nucl. 56 (2025) 3, 921-927
11) Feasibility study of anisotropic flow measurements with the fixed-target mode of the MPD experiment at NICA, Petr Parfenov, Taranenko A., Int. J. Mod. Phys. E (2026) 2641021
12) Status and initial physics performance studies of the MPD experiment at NICA, Abgaryan V., Petr Parfenov et. al., Eur.Phys.J.A 58 (2022) 7, 140
13) MPD physics performance studies in Bi+Bi collisions at $\sqrt{s_{NN}}$ = 9.2 GeV, Abdulin R., Petr Parfenov et. al., Rev.Mex.Fis. 71 (2025) 4, 041201

Centrality

Model study

v_2 fluctuations and correlation with [p_T]

Approbation (STAR)

MPD performance

Доклады на международных конференциях

1) ICPPA-2018, Energy deposition and anisotropic flow comparative analysis using FHCal in MPD experiment (NICA)
2) ISHEPP-2018, Performance studies of anisotropic flow with MPD at NICA
3) AYSS-2019, Performance studies of anisotropic flow with MPD at NICA
4) WPCF-2019, Elliptic and triangular collective flow of identified charged hadrons in Au+Au at $\sqrt{s_{NN}}$ = 200 GeV
5) ICNFP-2020, Elliptic and triangular collective flow of identified charged hadrons in Au+Au at $\sqrt{s_{NN}}$ = 200 GeV
6) ICPPA-2020, Elliptic (v_2) and triangular (v_3) anisotropic flow of identified hadrons from the STAR Beam Energy Scan program
7) NUCLEUS-2020, The comparison of methods for anisotropic flow measurements with the MPD Experiment at NICA
8) FANI-2020, Centrality determination in MPD at NICA: Glauber model application
9) NUCLEUS-2021, Anisotropic flow at energies $\sqrt{s_{NN}}$ = 2-11 GeV
10) FANI-2021, Model comparison with experimental data on collective flow at FAIR and NICA energies
11) NUCLEUS-2022, Model study of the energy dependence of the correlation between anisotropic flow and the mean transverse momentum in Au+Au collisions
12) ICPPA-2022, Scaling properties of anisotropic flow at Nuclotron-NICA energies
13) NICA-2022, Model comparison with experimental data on collective flow at FAIR and NICA energies
14) ISHEPP-2023, Performance study of the anisotropic flow measurements of identified charged hadrons with fixed-target mode of the MPD experiment at NICA
15) LomCon-2023, Anisotropic flow and its scaling properties at Nuclotron-NICA energies
16) AYSS-2023, Feasibility study for anisotropic flow measurements of identified charged hadrons with fixed-target mode of the MPD experiment at NICA
17) HEP&FT-2024, Anisotropic flow and correlations at the MPD experiment
18) The 2-nd China-Russia Joint Workshop on NICA Facility, MPD performance in the fixed-target mode
19) ICPPA-2024, Status of the MPD experiment at NICA
20) NUCLEUS-2025, Feasibility study of the anisotropic flow measurements with fixed-target mode of the MPD experiment at NICA
21) ISHEPP-2025, Anisotropic flow in asymmetric Xe+W collisions at MPD-FXT

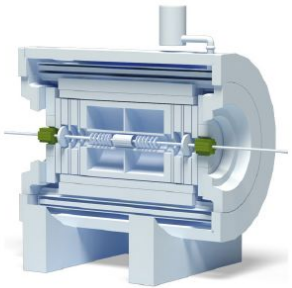
Some notable contributions…

NICA

Technical Design Report for the MPD Experiment

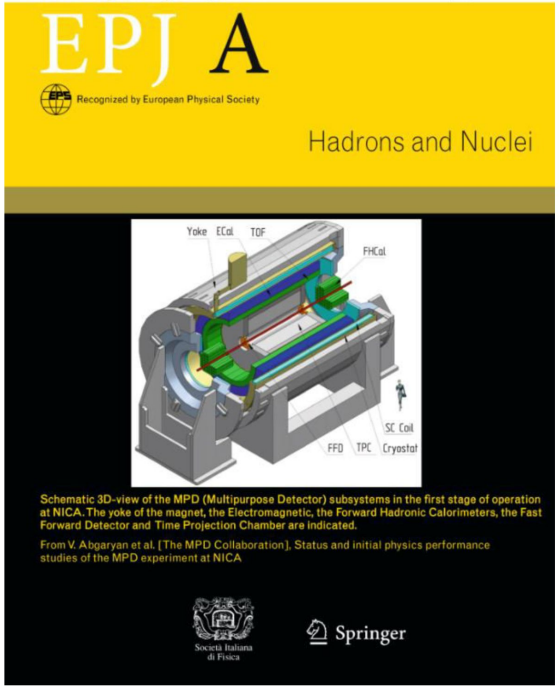
Nuclotron Based Ion Collider Facility

Forward Hadron Calorimeter (FHCal)



June 2018

1st Collaboration paper



2st Collaboration paper



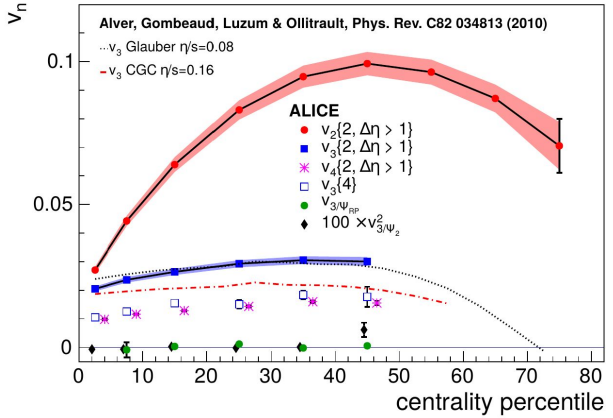
Nuclear Physics Revista Mexicana de Física **71** 041201 1–45 JULY-AUGUST 2025

MPD physics performance studies in Bi+Bi collisions at $\sqrt{s_{NN}} = 9.2$ GeV

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Fomenko[19], M.A. Gaganova[16], K.A. Galaktionov[28], Yu.D. Galkin[27], A.S. Galoyan[16], Ch. Gao[17], P.E. García-González[15], O.P. Gavrishuk[19], N.S. Gerakstan[28], S.E. Gerasimov[16], K.V. Gertsenberger[16], N. Gevorgyan[1], Y. Ghonemim[16], O. Golosov[19], V.M. Golovatyuk[16], M. Golubeva[16], A.O. Golunov[16], I. Goncharov[22], N.V. Gorbunov[16], P. Gordeev[19], I.P. Gorelikov[16], H. Grigorian[1], P.N. Grigoriev[16], F. Guber[10], D. Guo[17], A.V. Guskov[16], D. Han[34], W. Han[17], W. He[7], L.A. Hernández-Rosas[5], M. Herrera[5], S. Hnatic[16], M. Hnatič[23], M. Huang[20], S.A. Ibraimova[12], D.M. Idrisov[19], T.K. Idrisova[12], Z.A. Igamkulov[16], S.N. Igolkin[28], A.Yu. Isupov[16], D. Ivanishchev[20], A.V. Ivanov[16], A. Ivashkin[10], J. Jiao[20], I. Jadochnikov[1], S.I. Kakurin[16], N.I. Kalinichenko[28], A. Kamkin[25], M.N. Kapishin[16], D.E. Karmanov[21], N. Karpushkin[10], I.A. Kashunin[16], Y. Kasumov[22], A.O. Kechechyan[16], G.D. Kekelidze[16], V.D. 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Lokhtin[21], J.R. Luksties[16], D. Larionova[24], A. Lobanov[24], P. Lu[35], I. Luna-Reyes[15], X. Luo[17], Y. Ma[7], D.T. Madigozhin[16], A.A. Makarov[16], V.I. Maksimenkova[16], A.I. Malakhov[16], M. Malaev[20], I.A. Maldonado-Cervantes[16], V. Malev[20], I.V. Malikov[16], N.A. Maltsev[28], N.A. Makarov[28], M. Maksimov[20], M.A. Martemianov[19], P. Martínez-Torres[15], M.A. Matsyuk[19], M. Medvedeva[27], D.I. Melikov[31], D.G. Melnikov[16], M.M. Merkin[21], S.P. Mertz[16], I.N. Meshkov[16], V.V. Mialkovski[16], I.I. Migulina[16], K.R. Mikhaylov[16,20], G.D. Milnov[16], J. Milosevic[27], Yu.I. Minaev[16], S.A. Mituxin[16], G.V. Mescheriakov[16], N.A. Molokanova[16], S. Morozov[21], A.A. Moshkin[16], S.A. Movchan[16], A.N. Moybenko[16], K.A. Mukhin[16], Yu.A. Murin[21], S. Musin[21], G.G. Musulmanbekov[16], V.V. Mytsin[16], E.E. Muraykin[16], L. Nadderd[37], R.V. Nagdasev[16], Yu. Naryshkin[20], A.V. Nechaevskiy[16], V.A. Nikitin[16], V.A. Novoselov[16], I.A. Olexs[16], A.G. Olshevski[16], O.E. Orlov[16], V. Papoyan[1], P.E. Parfenov[16,21], S.S. Pargicky[16], M.E. Patiño-Salazar[14], S.V. Patronova[16], V.A. Pavlyukevich[16], I.S. Pelevanyuk[16], V.A. Penkin[16], D. Peresunko[19], D.V. Peshekhonov[16], V.A. Petrov[15], V.V. Petrov[28], A.V. Piliar[16], A. Piloyan[1], S.M. Piyadin[16], M.N. Platonova[31], D.V. Podgainy[16], M. Pokidova[20], V.N. Popov[28], D.S. Potapov[16], D.S. Prokhorova[28], N.A. Prokofiev[28], D.I. Priakhina[16], I. Pshenichnov[10], A.M. Puchkov[28], N. Pukhaeva[22,16], A. Pyatigor[2], J. Qin[35], F. Ratnikov[8], A. Raya[15], V. Rekovic[37], M. Reyes-Gutiérrez[15], S. Reyes-Peña[16], A. Riabov[20], V. Riabov[20], Yu. Riabov[20], S.P. Rode[16], A. Rodríguez-Alvarez[16], O.V. Rogachevsky[16], V.Yu. Rogov[16], V.A. Rudnev[28], I.A. Rufanov[16], M.M. Rumyantsev[16], I. Rudziankou[32], Yu. Rusak[32], A.A. Rybakov[16], Z. Sadygov[16], A.U. Sánz-Trujillo[4], V.A. Samsonov[16], A.A. Savenkov[16], S. Savenkov[10], S.A. Sedykh[16], T.V. Semchukova[16], A.Yu. Semenov[16], I.A. Semenova[16], V.Z. Serdyuk[18], S.V. Sergeev[16], A.S. Serikkanov[17], E.V. Serochkin[19], Yu. Shafarevich[27], D. Shapaev[24], O.M. Shaposhnikova[28], L.M. Shcheglova[31], M.F. Shopova[20], D.V. Shchegolev[16], A.V. Shchipunov[16], Y. Shen[29], A.D. Sheremetiev[16], A.I. Sheremetieva[16], S. Shi[17], M.O. Shitenkov[16], E.E. Shmanay[27], S.V. Shmatov[16], I.A. Shmyrev[16], A.A. Shunko[16], A.V. Shutov[16], V.B. Shutov[16], A.O. Sidorin[16], S.V. Simak[28], I.V. Slepnev[16], V.M. Slepnev[16], I.P. Slepo[16], I.A. Smelyanskiy[16], A.M. Snigirev[31], O.V. Sobol[28], A.N. Solomin[31], A.S. Soria[16], G.G. Stiforov[16], L.Yu. Stolypina[16], E.A. Streletskaya[16], O.I. Streltsova[16], M. Strikhanov[21], T.A. Strizh[16], A. Strizhak[10],

Motivation for centrality determination

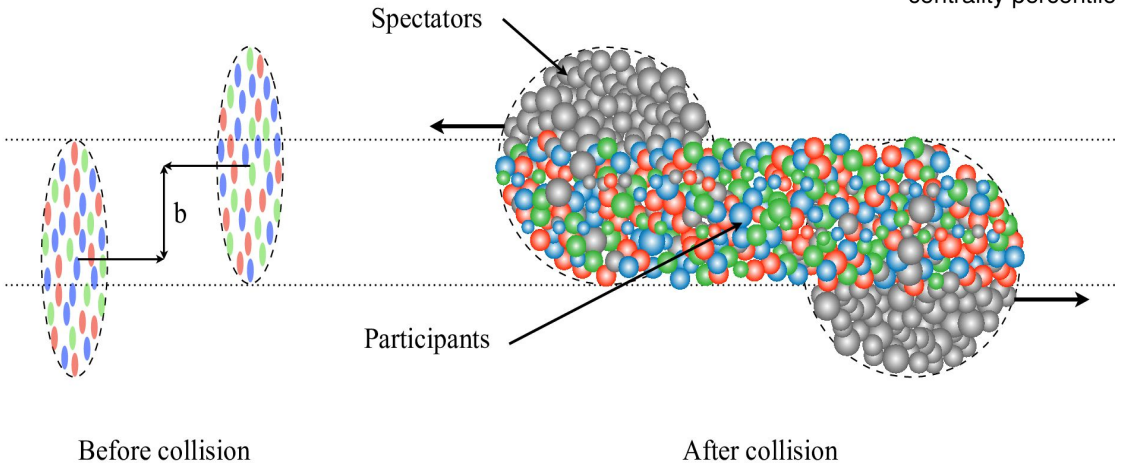
J.Phys.G 38 (2011) 124013



- Evolution of matter produced in heavy-ion collisions depends on its initial geometry
- Impact parameters (**b**) - one of the important collision parameters
  - impossible to measure experimentally
- **Goal of centrality determination:** map (on average) the collision geometry parameters to experimental observables (centrality estimators)

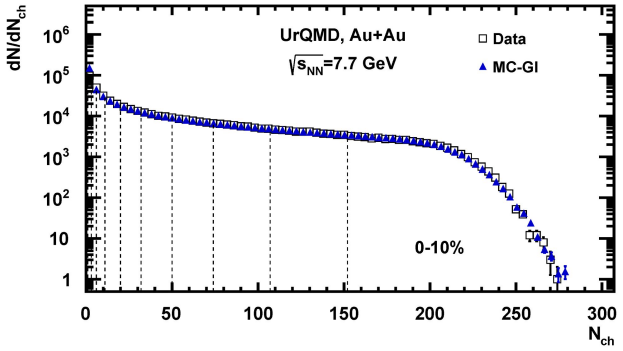
Centrality class S_1-S_2:
group of events corresponding to a given fraction (in %) of the total cross section:

$$C_S = \frac{1}{\sigma_{inel}^{AA}} \int_{S_1}^{S_2} \frac{d\sigma}{dS} dS$$



Centrality determination based on MC Glauber

Petr Parfenov et. al., Particles 4 (2021) 2, 275-287



For **multiplicity of produced particles** used in STAR, HADES, …

Get (b, N_{part}, N_{coll}) from MC-Glauber

Evaluate number of ancestors (sources of produced particles)
$N_a = fN_{part} + (1-f)N_{coll}$

Sample multiplicity of produced particles (S_i) N_a times from NBD(μ, **k**)

Multiplicities from two collision events are randomly superimposed with the probability **p** (“pileup” events)

Result: total S_{tot}

MC-Glauber distribution

Full Monte-Carlo (real data) distribution

Evaluate χ^2 between $N/dN_{MC/data}$ and N/dN_{Gl}

Scan phase space of parameters to find their values for minimum of χ^2

Extract relation between geometry parameters and centrality estimator

Link: https://github.com/FlowNICA/CentralityFramework

The Bayesian inversion method (Γ-fit)

Petr Parfenov et. al., Particles 4 (2021) 2, 275-287

Relation between multiplicity N_{ch} and impact parameter b is defined by the fluctuation kernel:

$$P(N_{ch}|c_b) = \frac{1}{\Gamma(k(c_b))\theta^k} N_{ch}^{k(c_b)-1} e^{-n/\theta} \qquad \frac{\sigma^2}{\langle N_{ch} \rangle} = \theta \simeq const,\ k = \frac{\langle N_{ch} \rangle}{\theta}$$

$$c_b = \int_0^b P(b')db' \text{ – centrality based on impact parameter}$$

Mean multiplicity as a function of c_b can be defined as follows:

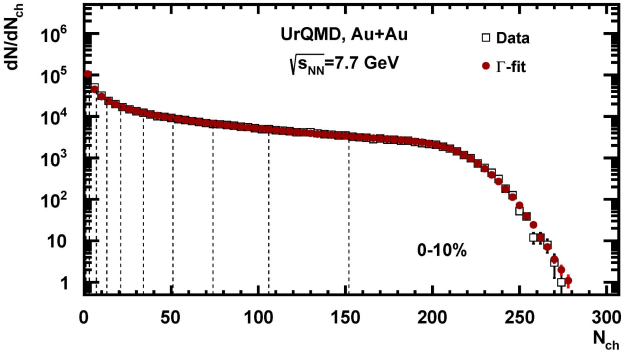
$$\langle N_{ch} \rangle = N_{knee} \exp\left(\sum_{j=1}^{3} a_j c_b^j \right) \qquad N_{knee}, \theta, a_j \text{ - 5 parameters}$$

Fit function for N_{ch} distribution:

$$P(N_{ch}) = \int_0^1 P(N_{ch}|c_b)dc_b$$

b-distribution for a given N_{ch} range:

$$P(b|n_1 < N_{ch} < n_2) = P(b)\frac{\int_{n_1}^{n_2} P(N_{ch}|b)dN_{ch}}{\int_{n_1}^{n_2} P(N_{ch})dN_{ch}}$$



2 main steps of the method:

Fit experimental (model) distribution with P(N)

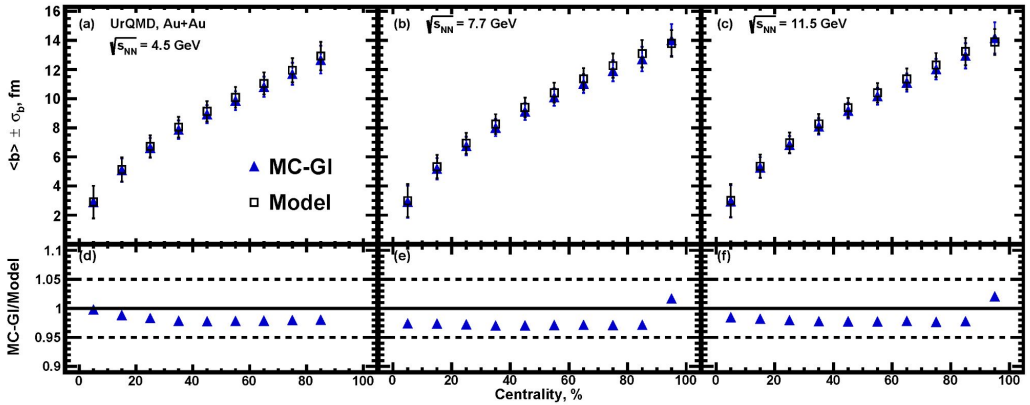
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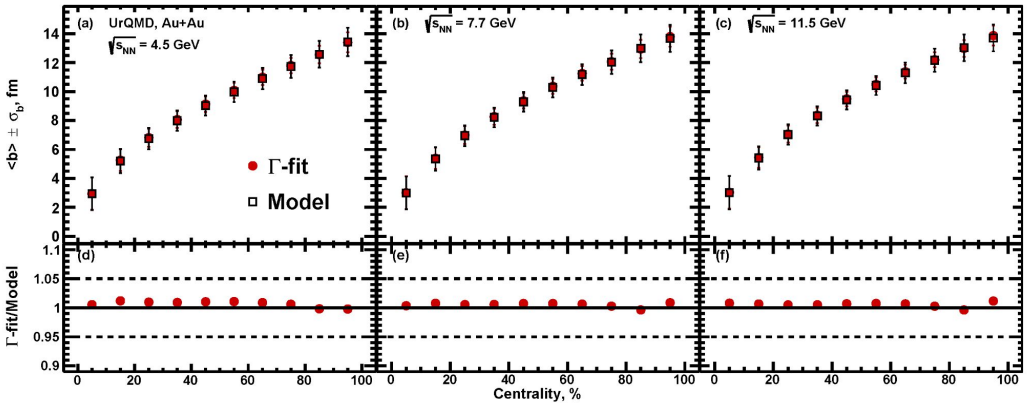
Construct P(b|E) using Bayes' theorem:
P(b|N) = P(b)P(N|b)/P(N)

Link: https://github.com/FlowNICA/CentralityFramework

Centrality determination methods: comparison

Petr Parfenov et. al., Particles 4 (2021) 2, 275-287





Methods applicability:
Both methods yield an estimate of <b> that agrees with the value extracted from the UrQMD model

hose methods can be used to compare v_2 from the MPD experiment with the results from the STAR experiment and from model prediction

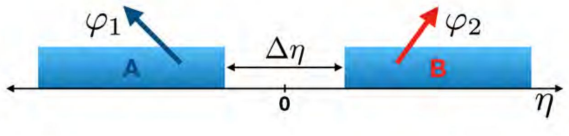
Methods for v_n measurements in MPD-CLD

Petr Parfenov et. al., Phys.Part.Nucl. 52 (2021) 4, 637-643
Petr Parfenov et. al., Particles 4 (2021) 2, 146-158
Petr Parfenov et. al., J.Phys.Conf.Ser. 1690 (2020) 1, 012129

- **Sub-event 2-particle Q-cumulants v2{2}:**

Δη=0.1 is applied between 2 sub-events A, B to suppress non-flow

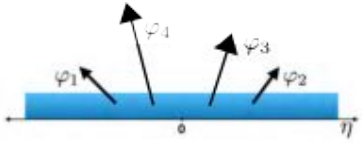
$$Q_n = \sum_{i=1}^{M} e^{in\phi} \qquad \langle 2 \rangle_{a|b} = \frac{Q_{n_a} Q^*_{n,b}}{M_a M_b} \qquad v_2\{2\} = \sqrt{\langle \langle 2 \rangle \rangle_{a|b}}$$



- **4-particle Q-cumulants v2{4}**

$$\langle 2 \rangle = \frac{|Q_n|^2 - M}{M(M-1)} \qquad v_2\{4\} = \sqrt[4]{2\langle \langle 2 \rangle \rangle^2 - \langle \langle 4 \rangle \rangle}$$

$$\langle 4 \rangle = \frac{|Q_n|^4 + |Q_{2n}|^2 - 2\Re[Q_{2n} Q^*_n Q^*_n] - 4(M-2)|Q_n|^2 - 2M(M-3)}{M(M-1)(M-2)(M-3)}$$

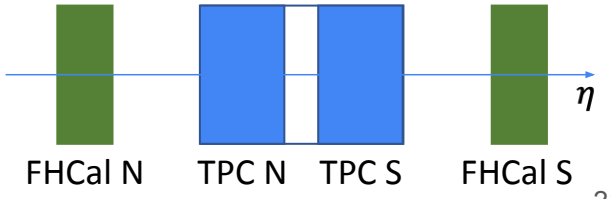


- **Event plane method:** Δη=0.1

$$Q_{n,x} = \sum_i w_i \cos(n\phi_i) \qquad Q_{n,y} = \sum_i w_i \sin(n\phi_i)$$

$$\Psi_n^{EP} = \frac{1}{n}\tan^{-1}\left(\frac{Q_{n,y}}{Q_{n,x}}\right) \qquad v_n = \frac{\langle \cos[n(\phi - \Psi_n^{EP})] \rangle}{\sqrt{\langle \cos[n(\Psi_{n,a} - \Psi_{n,b})] \rangle}}$$

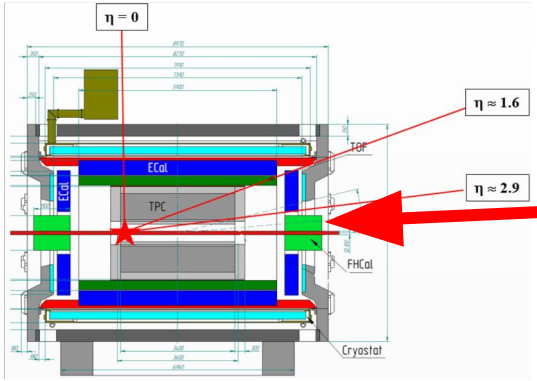
Here: ω_i - $p_{T,i}$ transverse momentum of the i-th track in the TPC
φ_i - azimuthal angle of the i-th track in the TPC
Ψ_n - event plane angles



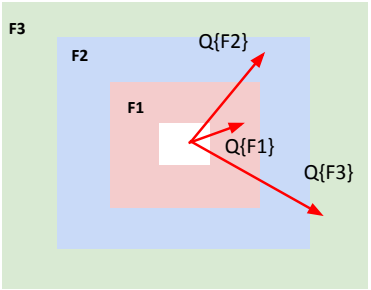
Link: https://github.com/FlowNICA/QCumulant

Flow vectors for the MPD-FXT

Petr Parfenov et. al., Phys.Part.Nucl. 56 (2025) 3, 921-927
Petr Parfenov et. al., Int. J. Mod. Phys. E (2026) 2641021



Modules of FHCal divided into 3 groups



From momentum of each measured particle define a u_n-vector in transverse plane:

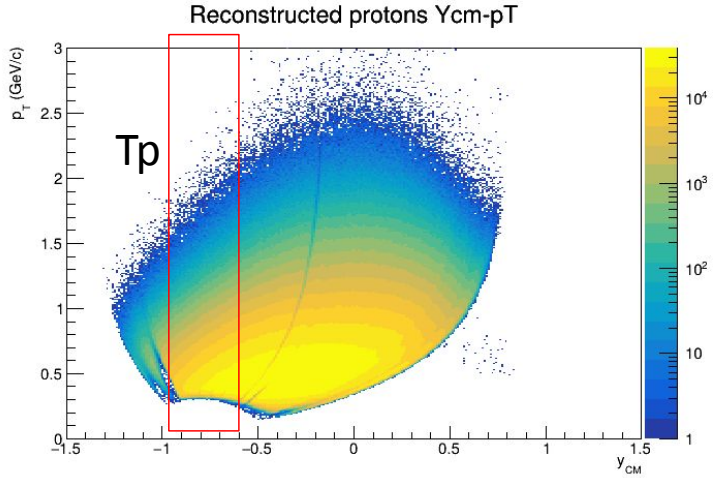
$$u_n = e^{in\phi}$$

where φ is the azimuthal angle

Sum over a group of u_n-vectors in one event forms Q_n-vector:

$$Q_n = \frac{\sum_{k=1}^{N} w_n^k u_n^k}{\sum_{k=1}^{N} w_n^k} = |Q_n| e^{in\Psi_n^{EP}}$$

Ψ_n^{EP} is the event plane angle



Additional subevents from tracks not pointing at FHCal:

Tp: p; -1.0<y<-0.6;

Flow methods for v_n calculation

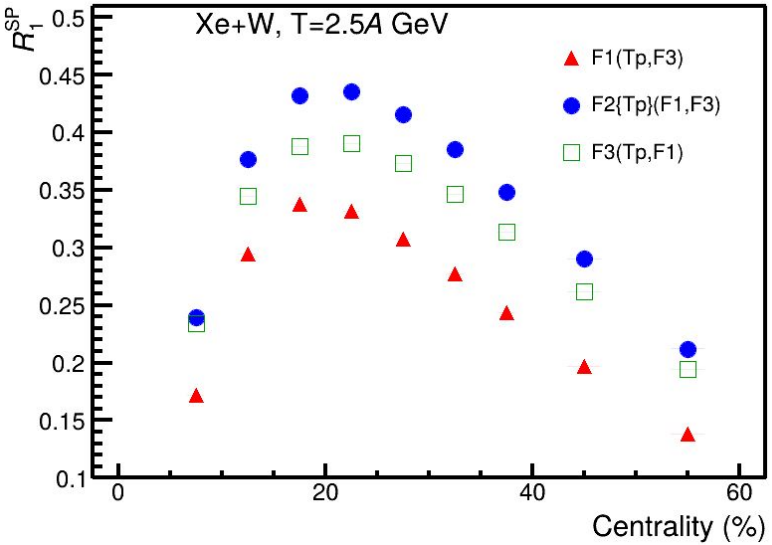
Petr Parfenov et. al., Phys.Part.Nucl. 56 (2025) 3, 921-927
Petr Parfenov et. al., Int. J. Mod. Phys. E (2026) 2641021

Scalar product (SP) method:

$$v_1 = \frac{\langle u_1 Q_1^{F1} \rangle}{R_1^{F1}} \qquad v_2 = \frac{\langle u_2 Q_1^{F1} Q_1^{F3} \rangle}{R_1^{F1} R_1^{F3}}$$

Where R_1 is the resolution correction factor

$$R_1^{F1} = \langle \cos(\Psi_1^{F1} - \Psi_1^{RP}) \rangle$$



Symbol “F2(F1,F3)” means R_1 calculated via (3S resolution):

$$R_1^{F2(F1,F3)} = \frac{\sqrt{\langle Q_1^{F2} Q_1^{F1} \rangle \langle Q_1^{F2} Q_1^{F3} \rangle}}{\sqrt{\langle Q_1^{F1} Q_1^{F3} \rangle}}$$

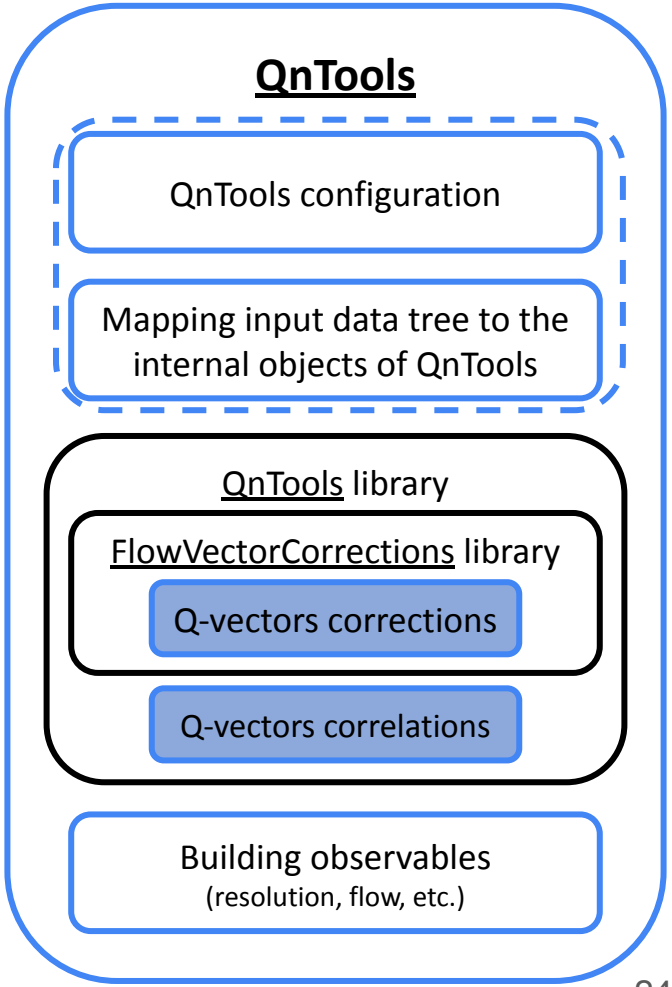
Symbol “F2{Tp}(F1,F3)” means R_1 calculated via (4S resolution):

$$R_1^{F2\{Tp\}(F1,F3)} = \langle Q_1^{F2} Q_1^{Tp} \rangle \frac{\sqrt{\langle Q_1^{F1} Q_1^{F3} \rangle}}{\sqrt{\langle Q_1^{Tp} Q_1^{F1} \rangle \langle Q_1^{Tp} Q_1^{F3} \rangle}}$$

Software solution: QnTools

Motivation:

- Decoupling configuration from implementation
- Persistency of analysis setup
- Co-existence of different setups (easy systematics study)
- Unification of analysis methods
- Self-descriptiveness of the analysis results



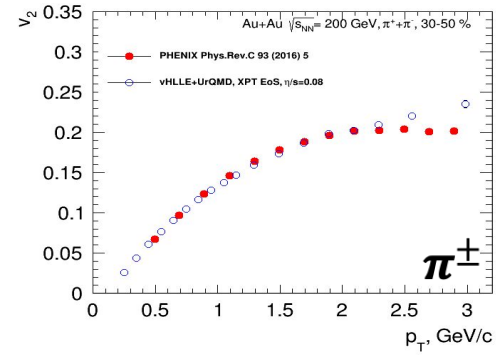
Petr Parfenov et. al., Phys.Part.Nucl. 56 (2025) 3, 921-927
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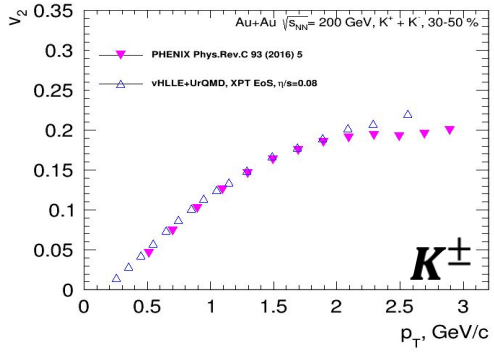
Git repository: https://github.com/FlowNICA/QnTools
Implementation for the MPD setup:
https://github.com/FlowNICA/qntools_macros

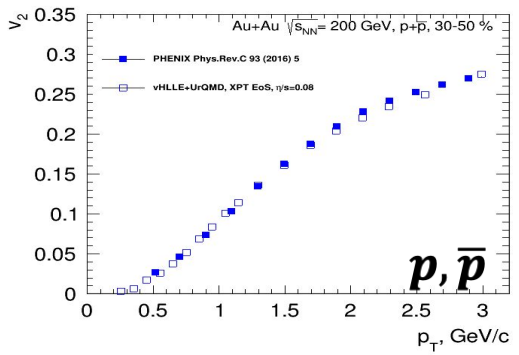
Continuing to develop implementation of QnTools-based package in the MPD experiment

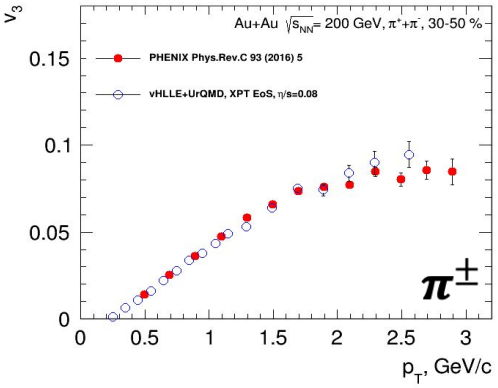
vHLLE+UrQMD: Elliptic and triangular flow in Au+Au collisions at 200 GeV

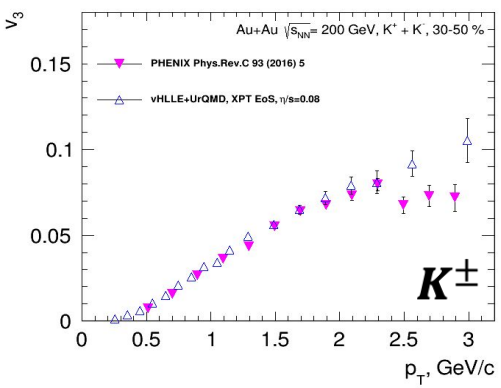
A. Demanov, Petr Parfenov, AIP Conf.Proc. 2377 (2021) 1, 030003

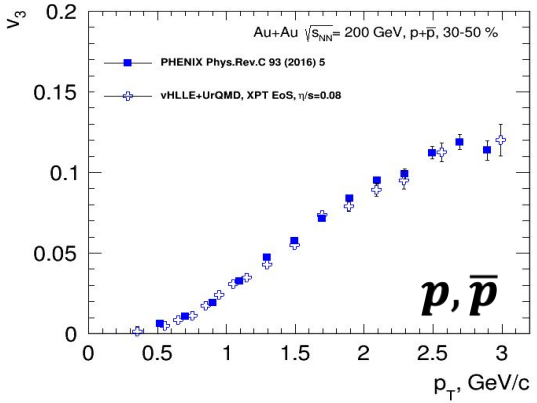










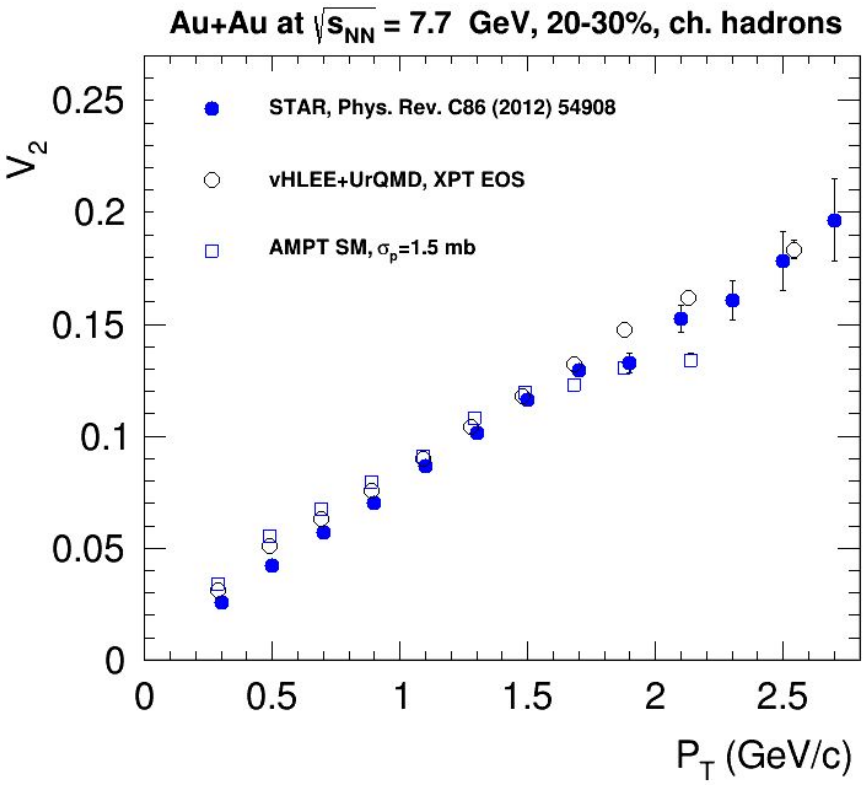


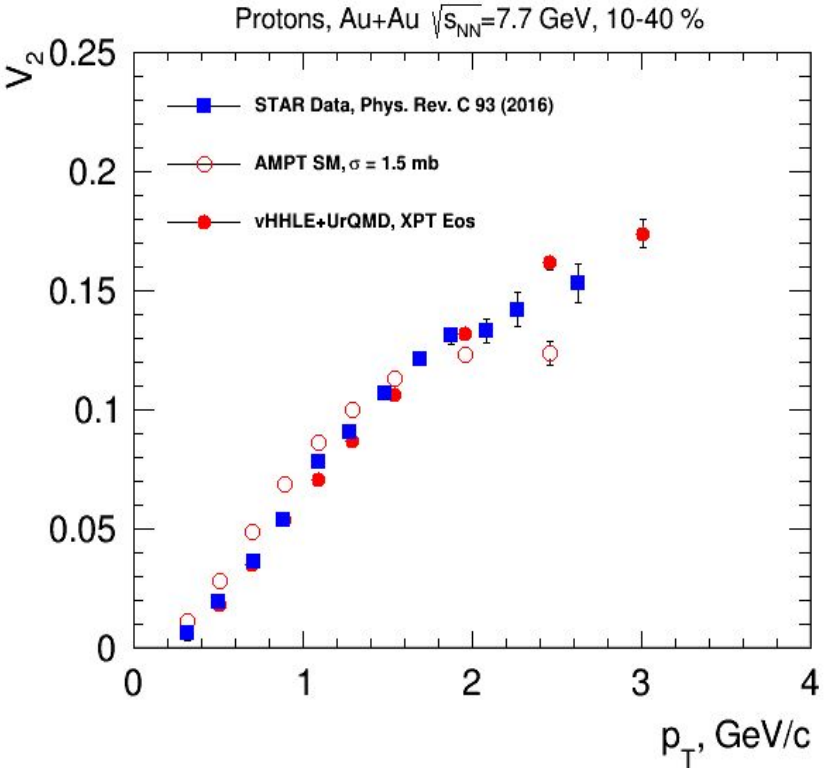
3D hydro model vHHLE + UrQMD (XPT EOS), $\eta/s = 0.08$ + param from Iu.A. Karpenko, P. Huovinen, H. Petersen, M. Bleicher , Phys.Rev. C91 (2015) no.6, 064901

Reasonable agreement between results of vHLLE+UrQMD model and published PHENIX data

Elliptic flow at NICA energies: Models vs. Data comparison

Petr Parfenov et. al., Phys.Part.Nucl. 51 (2020) 3, 309-313

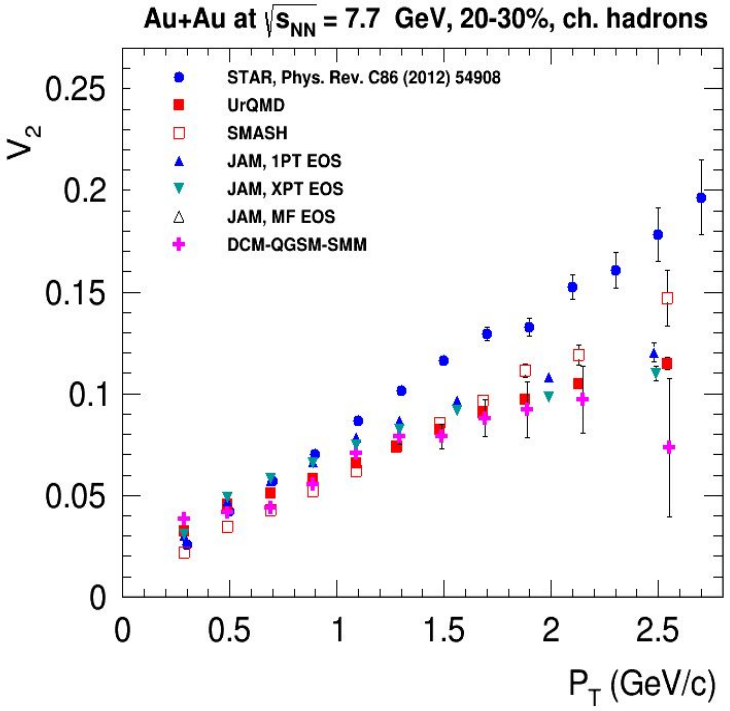


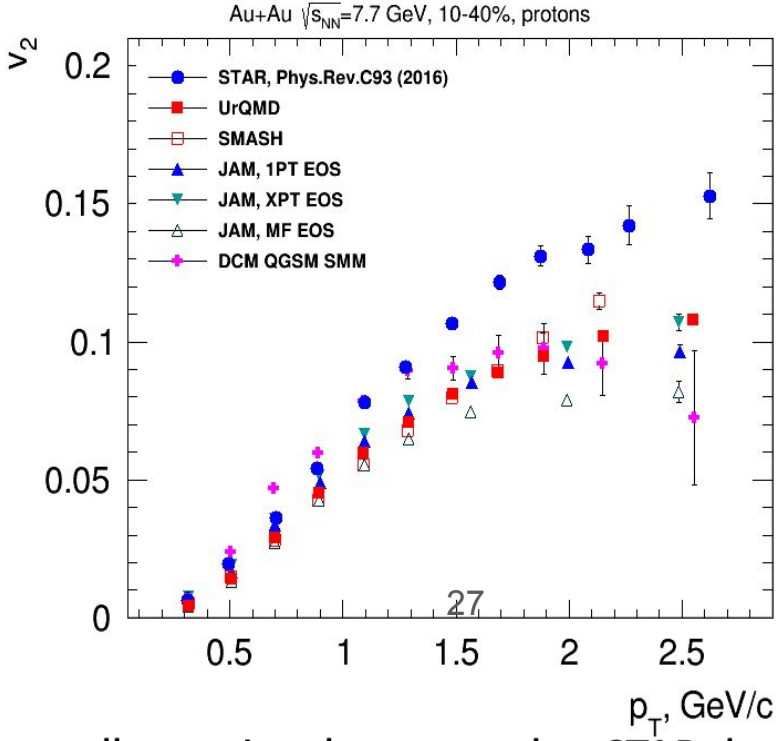


Good agreement between vHLLE+UrQMD (η/s= 0.2, XPT EOS), AMPT models and STAR data for $\sqrt{s_{NN}}$ ≥7.7 GeV

Elliptic flow at NICA energies: Models vs. Data comparison

Petr Parfenov et. al., Phys.Part.Nucl. 51 (2020) 3, 309-313

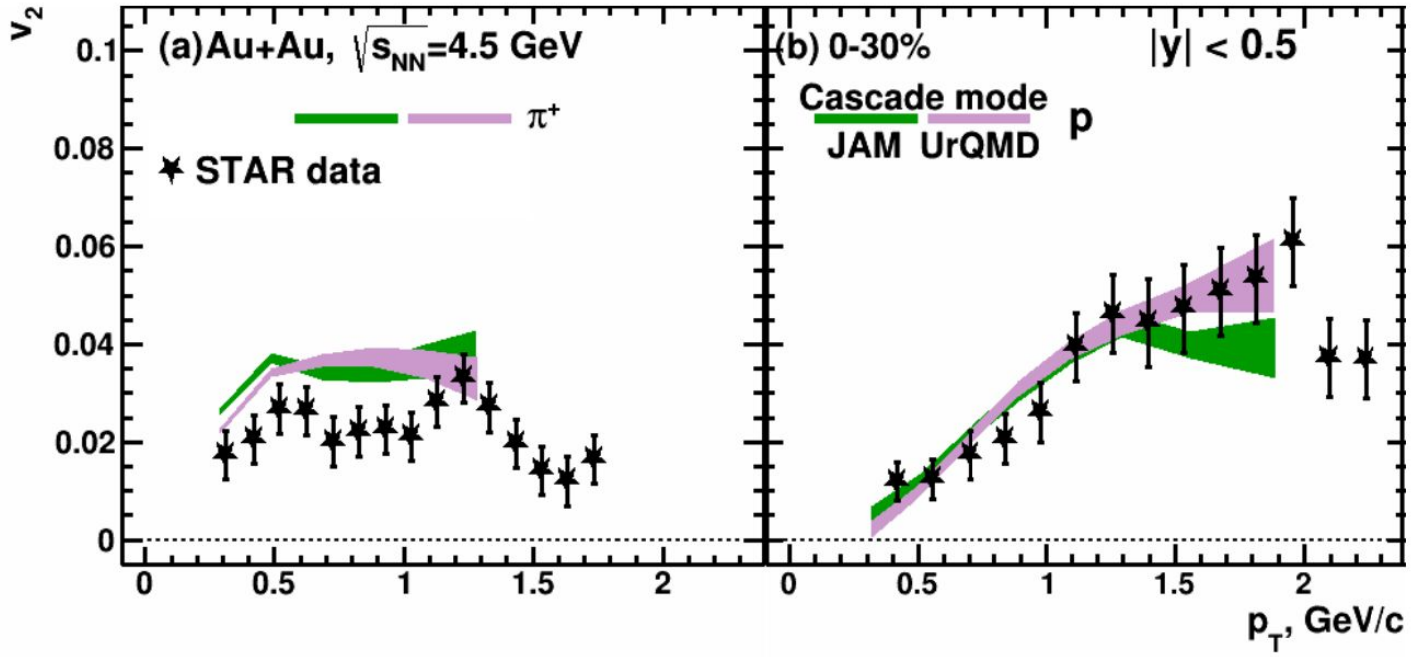




Pure String/Hadronic Cascade models give smaller v_2 signal compared to STAR data for $\sqrt{s_{NN}}$ ≥7.7 GeV

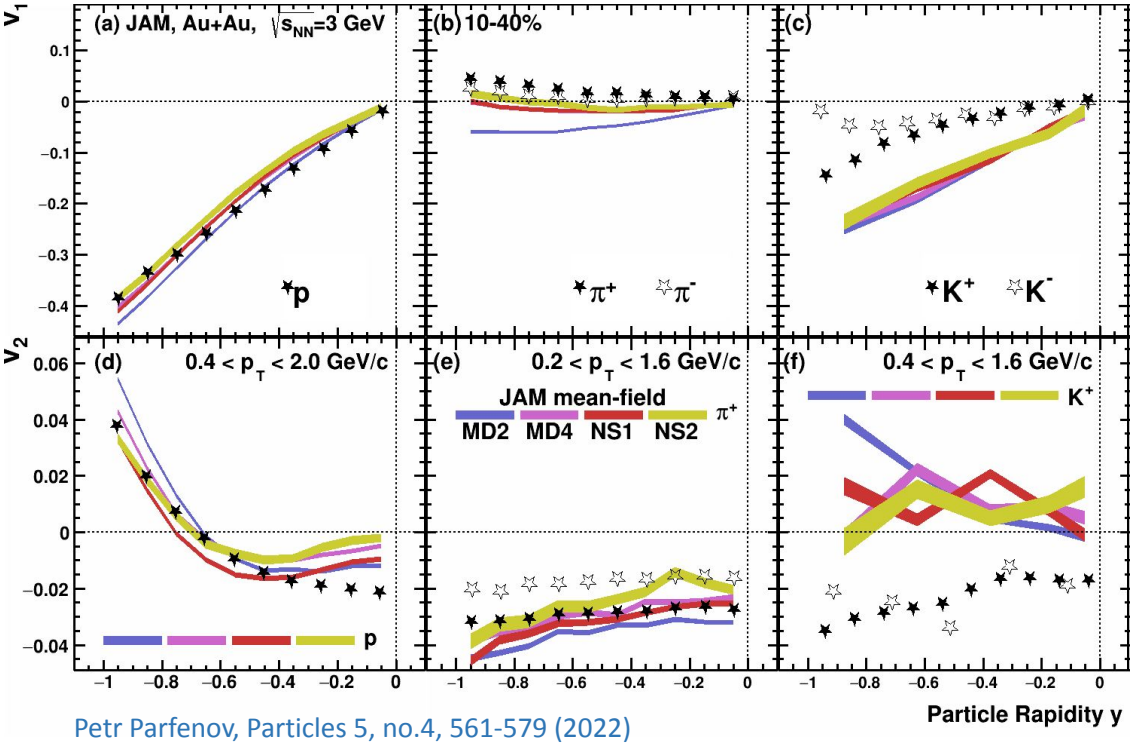
Elliptic flow at NICA energies: Models vs. Data comparison

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



Pure String/Hadronic Cascade models give similar v_2 signal compared to STAR data for Au+Au $\sqrt{s_{NN}}$ =4.5 GeV

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

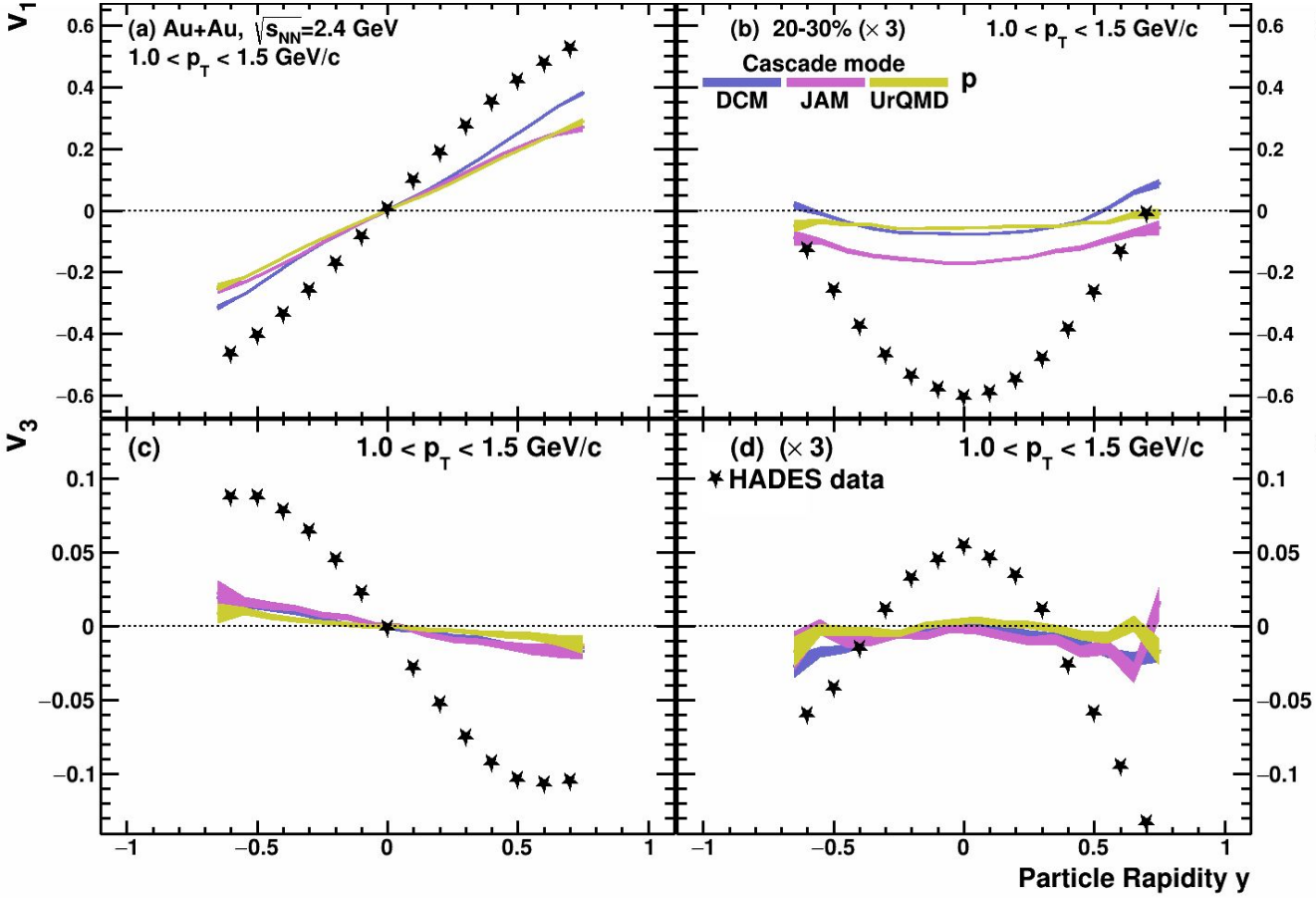


Petr Parfenov, Particles 5, no.4, 561-579 (2022)

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)

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

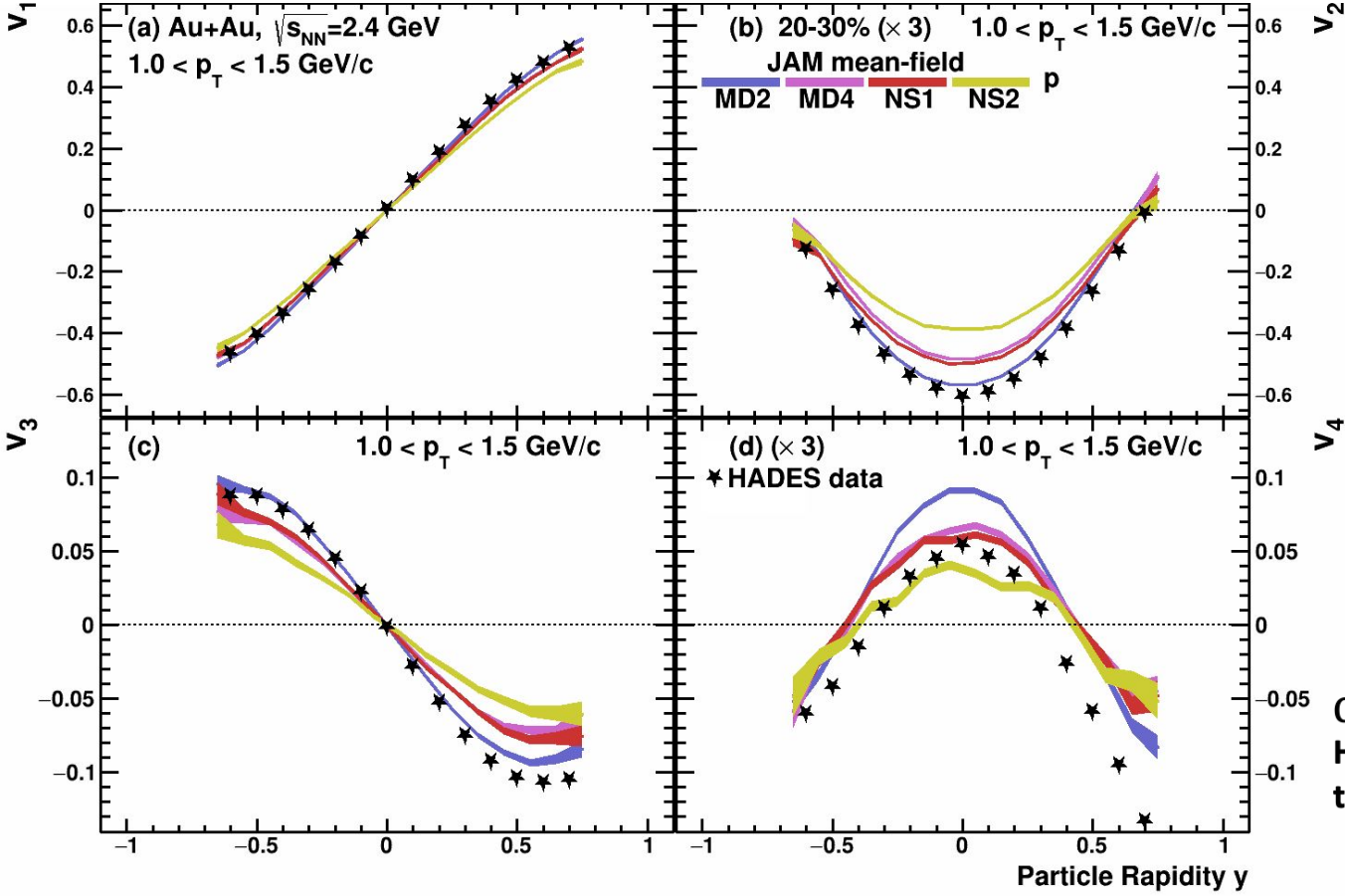


Petr Parfenov, Particles 5, no.4, 561-579 (2022)

Kinematic cuts:
$V_{1,3}(y)$: 1.0 < pT < 1.5 GeV/c
$V_{2,4}(y)$: 1.0 < pT < 1.5 GeV/c

Cascade models fail to reproduce HADES experimental data

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



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

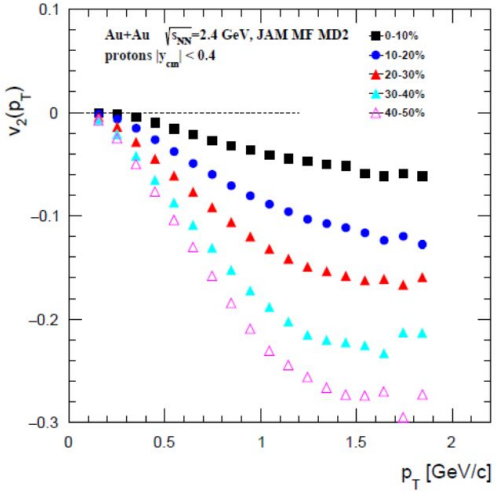
Kinematic cuts:
$V_{1,3}$(y): 1.0 < pT < 1.5 GeV/c
$V_{2,4}$(y): 1.0 < pT < 1.5 GeV/c

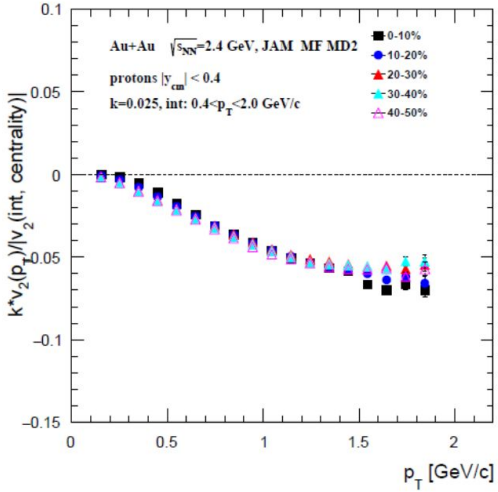
Good agreement for $v_n(y)$
Higher harmonics are more sensitive to different EOS than v_1

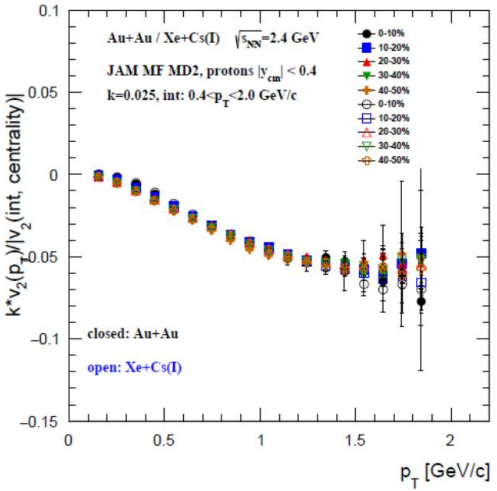
$|v_2^{int}|$ scaling: JAM MD2 model – Nuclotron energies

$v_n(\sqrt{s_{NN}}, R, \text{centrality}, \text{PID}, p_T, y) = v_n(\sqrt{s_{NN}}, R, \text{centrality}) \times v_n(\text{PID}, p_T, y)$

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



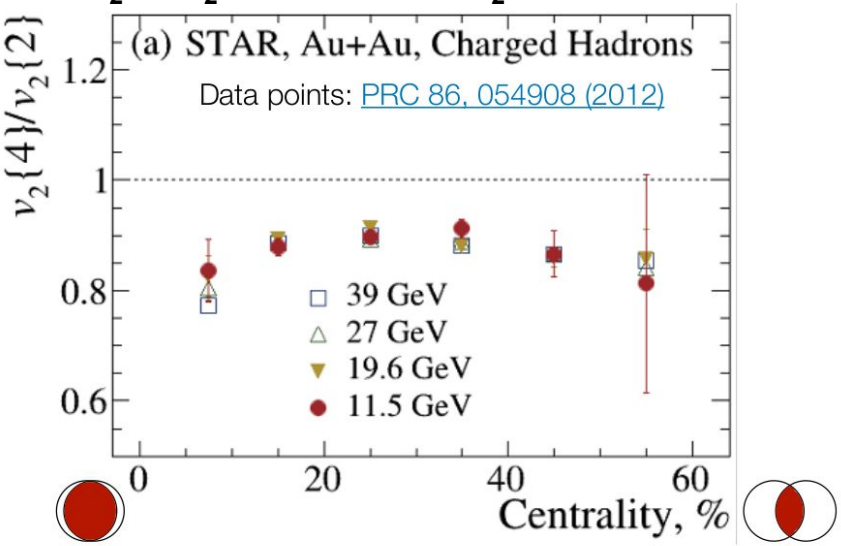




Scaling works for different centrality classes as well as for different collision systems
However, v_2^{int} scaling breaks around $\sqrt{s_{NN}}$= 3.3 GeV where v_2 changes sign

Study of v_2 fluctuation

$v_2\{4\}/v_2\{2\} \approx 1$: small v_2 fluctuations
$v_2\{4\}/v_2\{2\} \ll 1$: large v_2 fluctuations

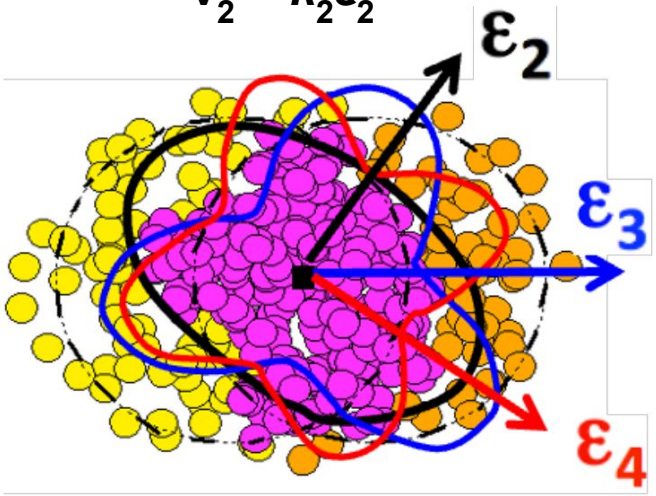


v_2 fluctuations at $\sqrt{s_{NN}} = 11.5 - 39$ GeV observed in STAR:

- Weak dependence on collision energy

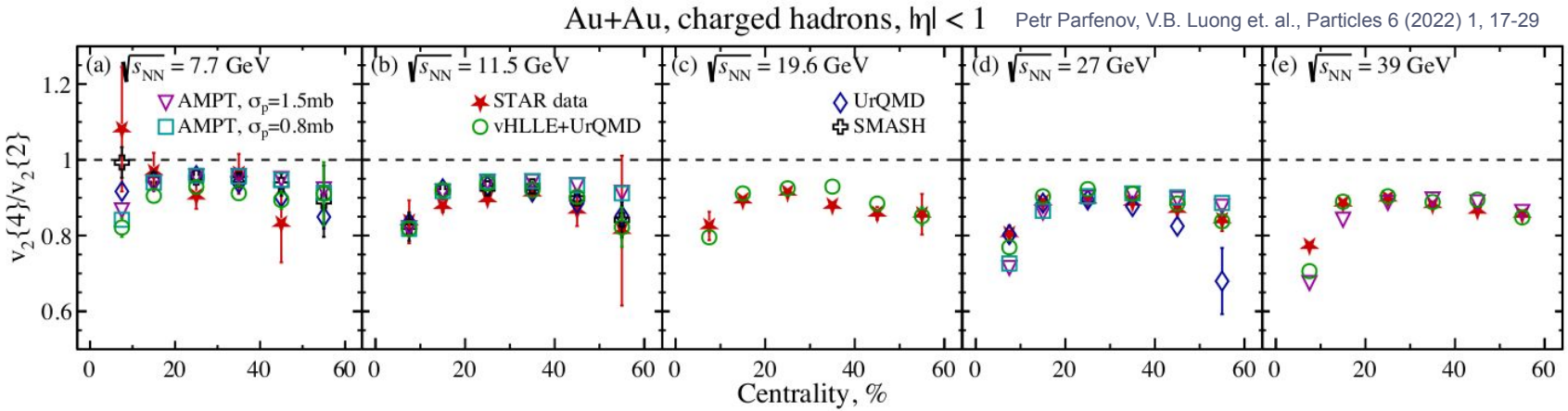
Petr Parfenov, V.B. Luong et. al., Particles 6 (2022) 1, 17-29

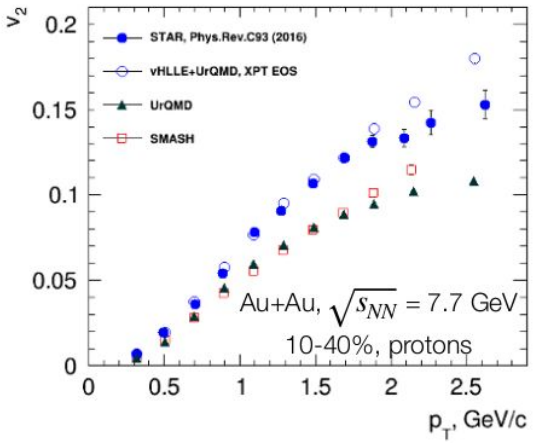
$v_2 = k_2\varepsilon_2$



- Indicate a dominated initial state driven fluctuations $\sigma\varepsilon_2$
- Provide constraints for IS models and shear viscosity η(T/s)

v_2 fluctuations at $\sqrt{s_{NN}}$ = 7.7 - 39 GeV

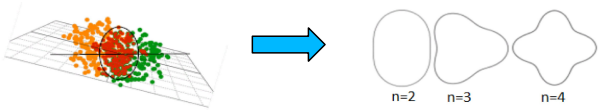




- At $\sqrt{s_{NN}}$ > 7.7 GeV pure string/cascade models without QGP phase underestimate v_2
- v_2 fluctuations observed in STAR can be reproduced by model either with or without partonic phase description
  - v_2 fluctuations dominated by ε_2 fluctuations
  - $v_2\{4\}/v_2\{2\}$: direct probe for the initial state conditions

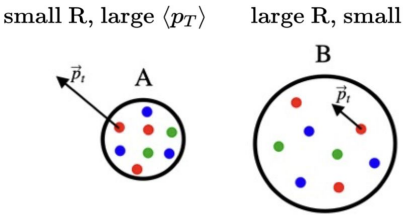
What about v2 fluctuations at lower energies?

$v_n - [p_T]$ correlation measurements



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

$v_n \propto \varepsilon_n, \qquad n = 1,2$



$\langle p_T \rangle \sim 1/R$

- v_n is sensitive to the initial shape of the collision geometry (but also thermalization, etc.)
- $[p_T]$ is sensitive to the initial size of the overlap region (but also thermalization, etc.)

$$\rho(\mathrm{v}_2^2,[p_T]) = \frac{\mathrm{cov}\left(\mathrm{v}_2^2,[p_T]\right)}{\sqrt{\mathrm{var}\left(\mathrm{v}_2^2\right)_{dyn}}\sqrt{c_k}}$$

$$\mathrm{cov}\left(\mathrm{v}_2^2,[p_T]\right) = \left\langle \frac{\sum_{A,C} e^{i\cdot 2\left(\varphi_1^A - \varphi_2^C\right)} \sum_B \left(p_{T,B} - \left\langle [p_T] \right\rangle\right)}{M_A M_C M_B} \right\rangle$$

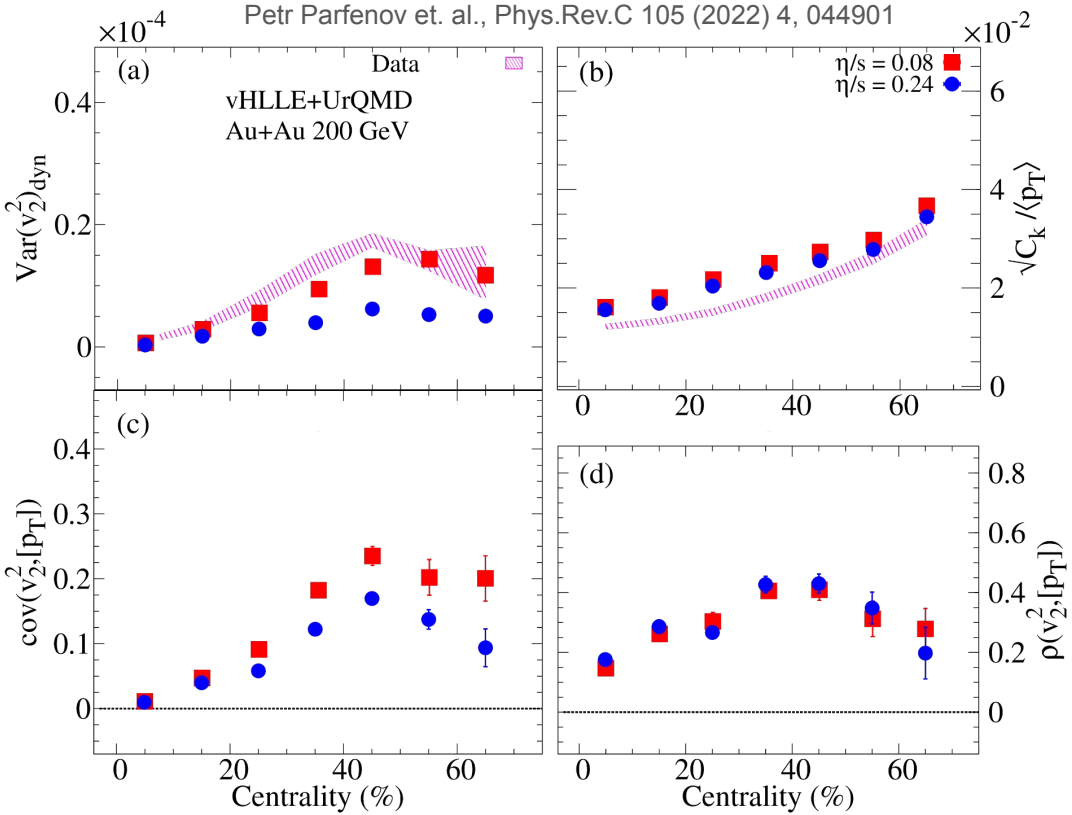
➢The $\rho(\mathrm{v}_2^2, [p_T])$ is sensitive to initial state and its entropy density profile

➢The $\mathrm{cov}(\mathrm{v}_2^2, [p_T])$ is sensitive to η/s

$$\mathrm{var}(v_2^2)_{dyn} = \langle v_2^4 \rangle - \langle v_2^2 \rangle^2 \qquad c_k = \left\langle \frac{1}{M_B(M_B-1)} \sum_B \sum_{B' \neq B} \left(p_{T,B} - \left\langle [p_T] \right\rangle\right)\left(p_{T,B'} - \left\langle [p_T] \right\rangle\right) \right\rangle$$

The precise set of measurements for $\mathrm{var}([p_T])$, $\mathrm{var}(v_2^2)$, $\mathrm{cov}(v_2^2, [p_T])$ and $\rho(v_2^2, [p_T])$ as a function of beam-energy and centrality could help precision extraction of the temperature and baryon chemical-potential dependence of η/s

v_2-[p_T] correlations: top RHIC energy

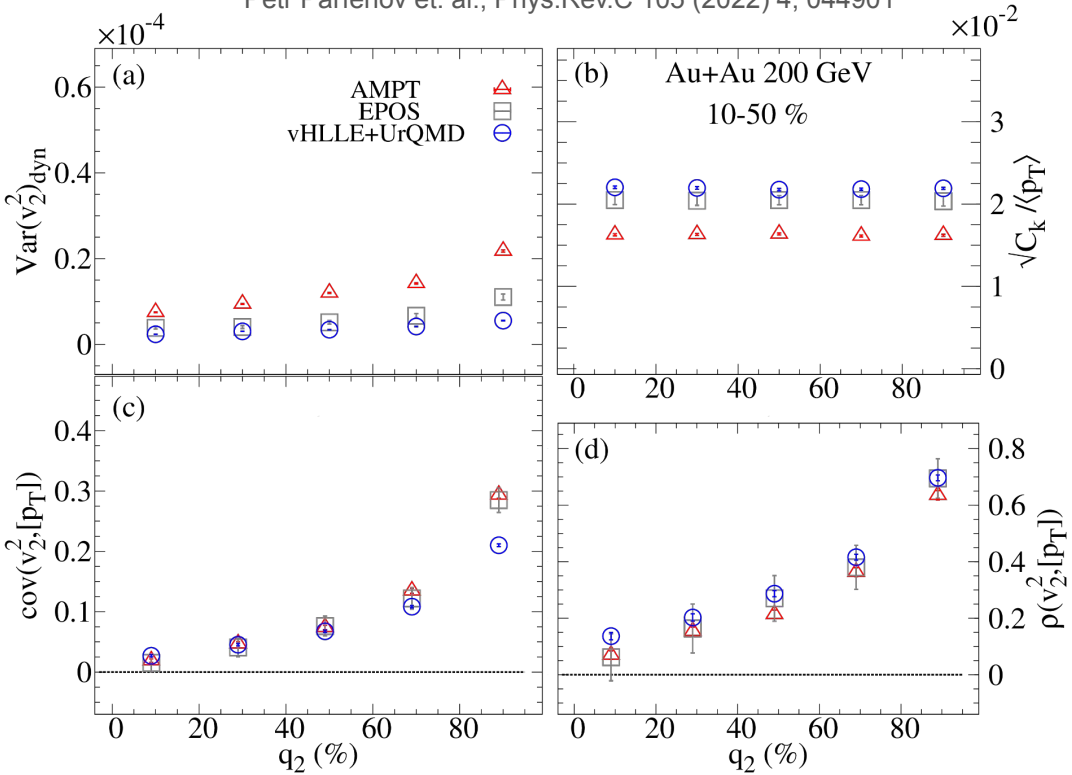


Same initial-state, different η/s:

- cov(v_2^2, [p_T]) and Var(v_2^2)$_{dyn}$ decrease with η/s
- ρ(v_2^2, [p_T]) and $\sqrt{C_k}$/<p_T> show weak dependence on η/s

v_2-[p_T] correlations: top RHIC energy

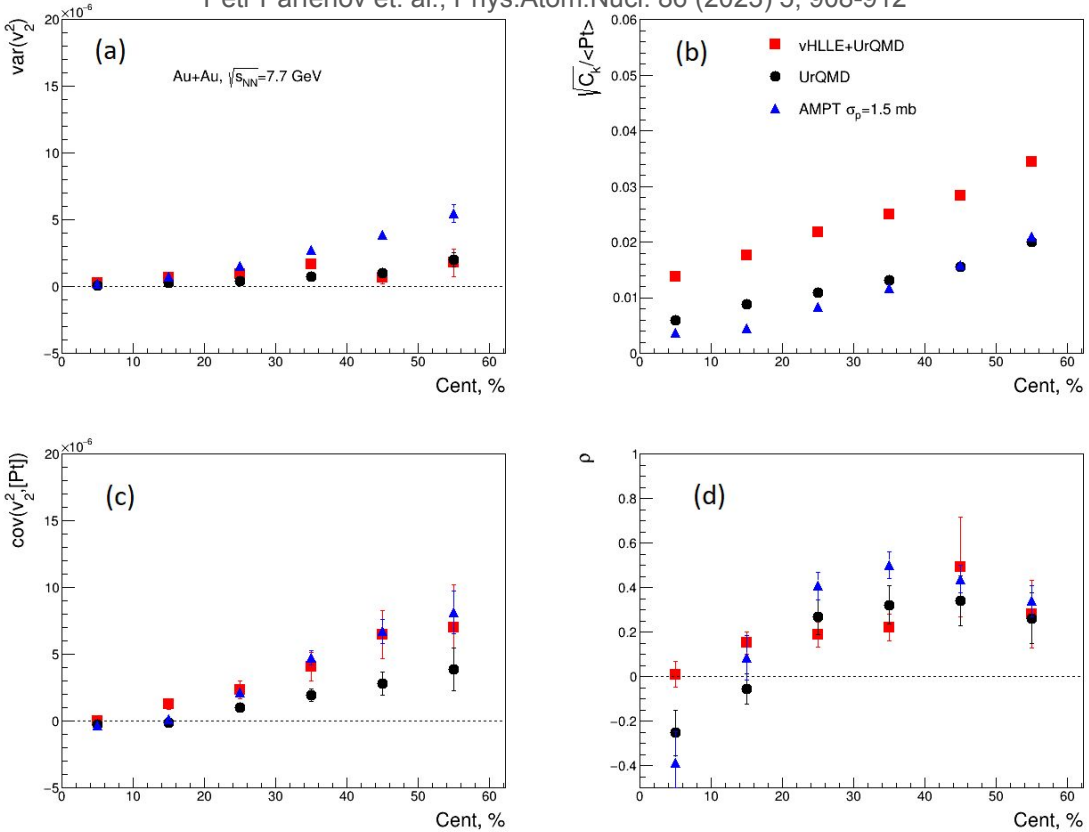
Petr Parfenov et. al., Phys.Rev.C 105 (2022) 4, 044901



cov(v_2^2, [p_T]) and $\rho(v_2^2, [p_T])$ show agreement between all models - similar initial- and final-state conditions in those models (AMPT, EPOS, vHLLE+UrQMD)

v_2-[p_T] correlations: NICA energy

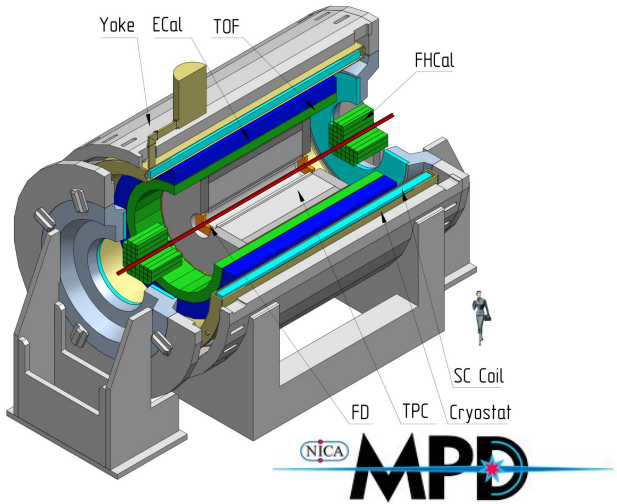
Petr Parfenov et. al., Phys.Atom.Nucl. 86 (2023) 5, 908-912



- Qualitatively: similar trends for all observables as in the case of 200 GeV
- Quantitatively: the differences are bigger between results from the models

The study of the correlation between v_2 and [p_T] will allow us to better understand the mechanisms of v_2 formation and its sensitivity to the initial and final conditions of the evolution of nuclear collisions

MPD and STAR experiments



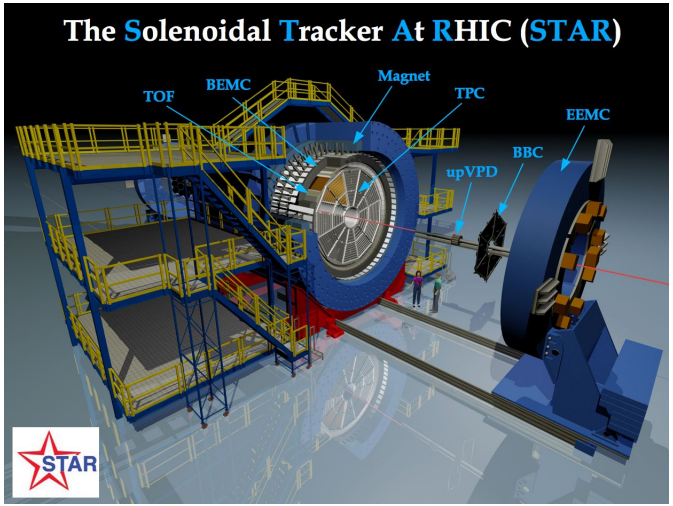
-5<η<-2

FHCal

-1.5<η<1.5
TPC
$0.2<p_T<3$ GeV/c

2<η<5

FHCal



-5<η<-3.3

BBC

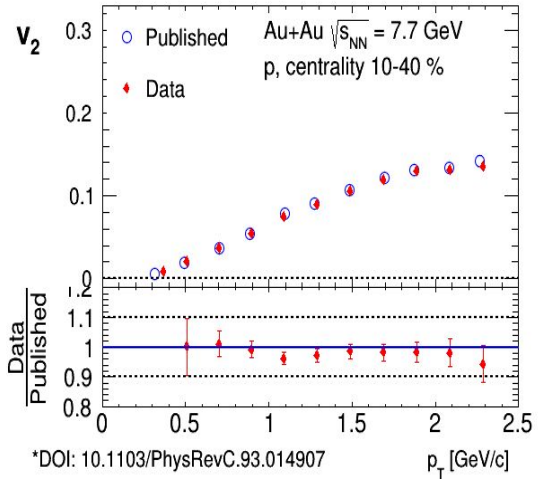
-1<η<1
TPC

3.3<η<5

BBC

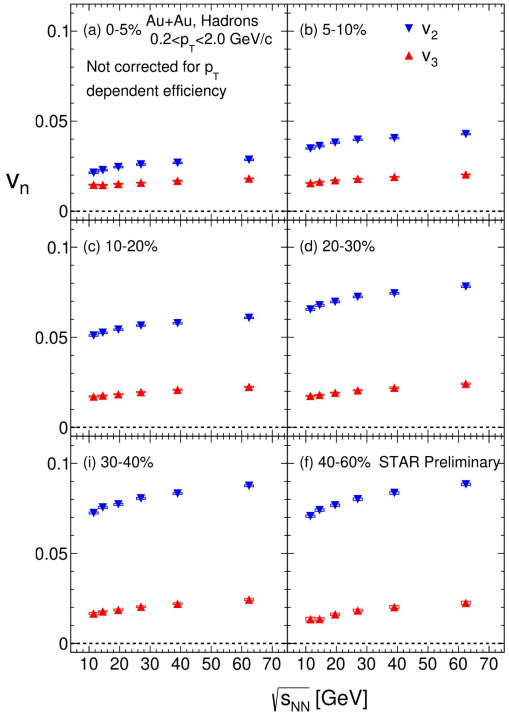
Both MPD and STAR have similar detector structure and overlap in the beam energy coverage

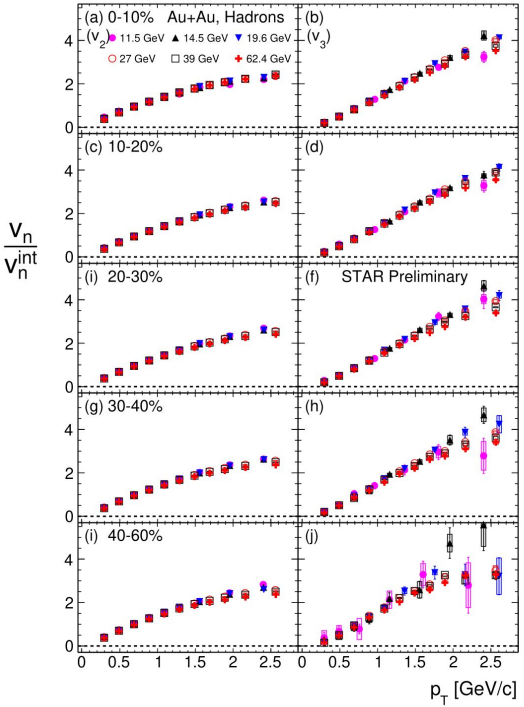
Testing developed methods for v_n measurements in STAR



Good agreement with previously published data

Petr Parfenov, J.Phys.Conf.Ser. 1690 (2020) 1, 012128

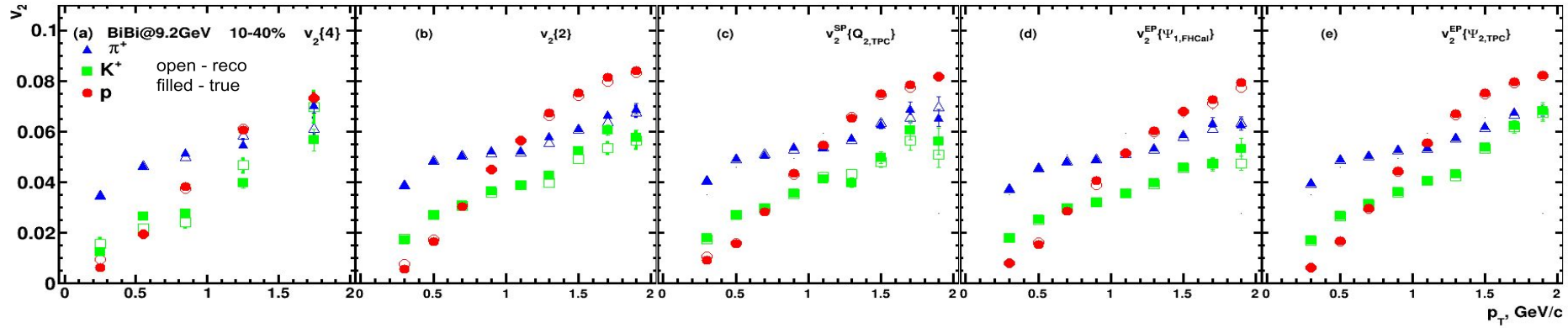


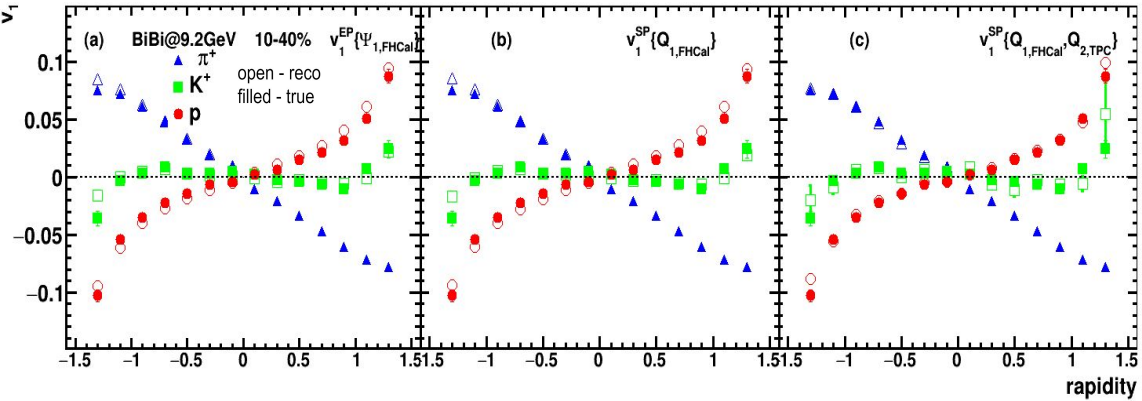


Developed methods were used in the analysis of the STAR experimental data

Flow performance: MPD-CLD

Petr Parfenov et. al., Rev.Mex.Fis. 71 (2025) 4, 041201

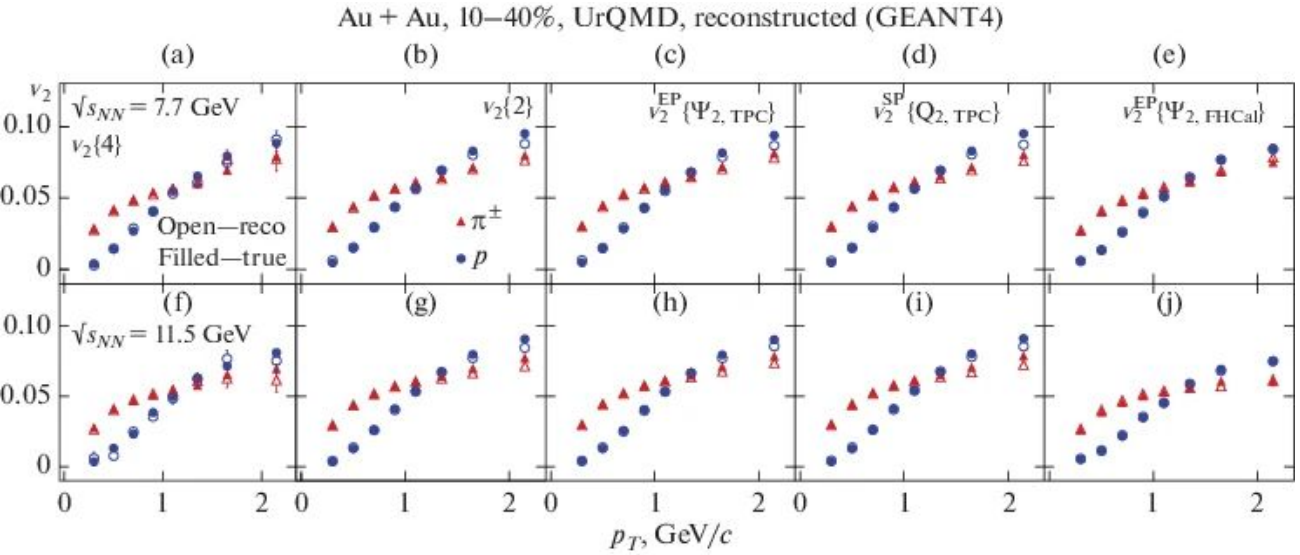


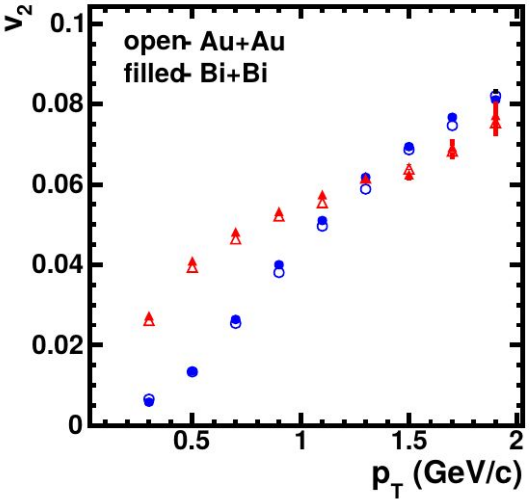


Good performance for flow measurements for all methods used

Flow performance: MPD-CLD

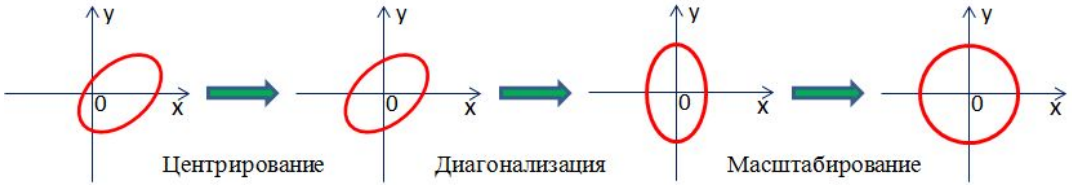
Petr Parfenov et. al., Phys.Part.Nucl. 52 (2021) 4, 637-643
Petr Parfenov et. al., Particles 4 (2021) 2, 146-158





Performance study was done for several beam energy points and collision systems

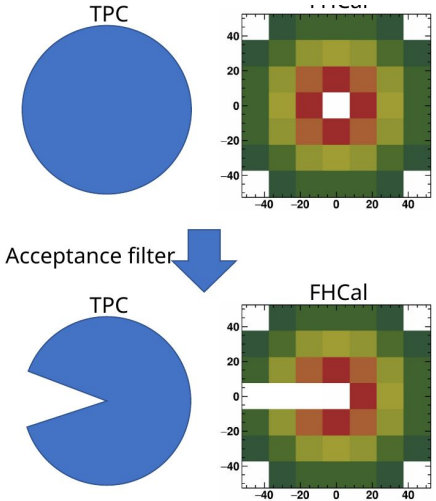
Corrections for non-uniform azimuthal acceptance

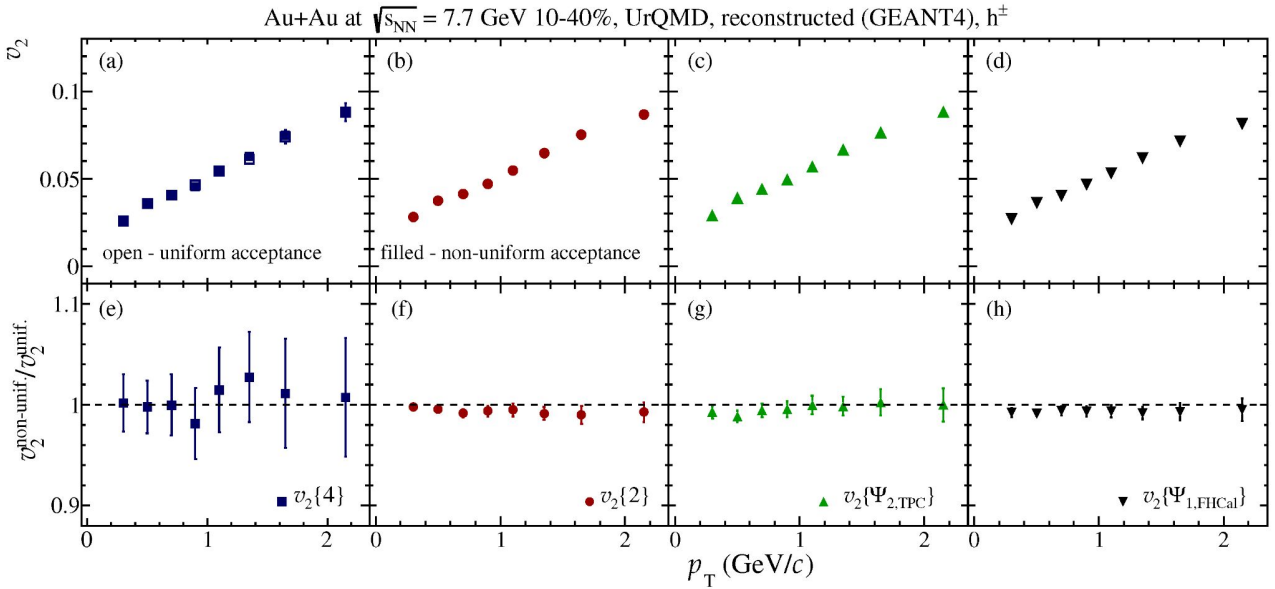


To suppress correlations caused by the detector's non-uniform acceptance, one an use a specific set of consecutive corrections:

Recentering, Twist, Rescale

Petr Parfenov et. al., Particles 6 (2022) 1, 17-29

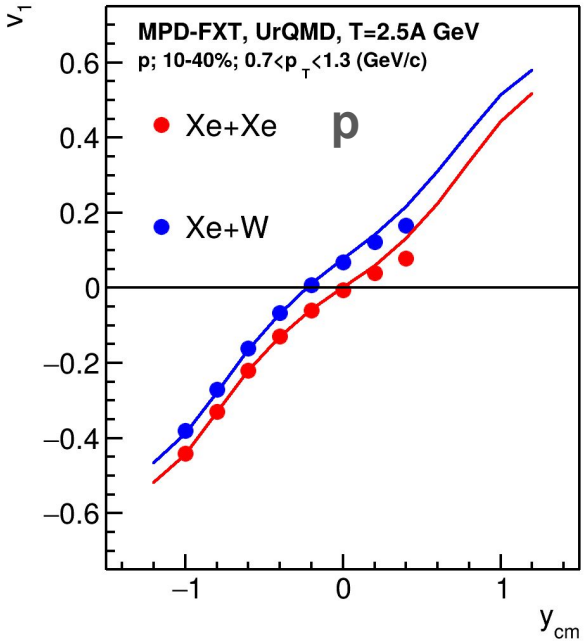


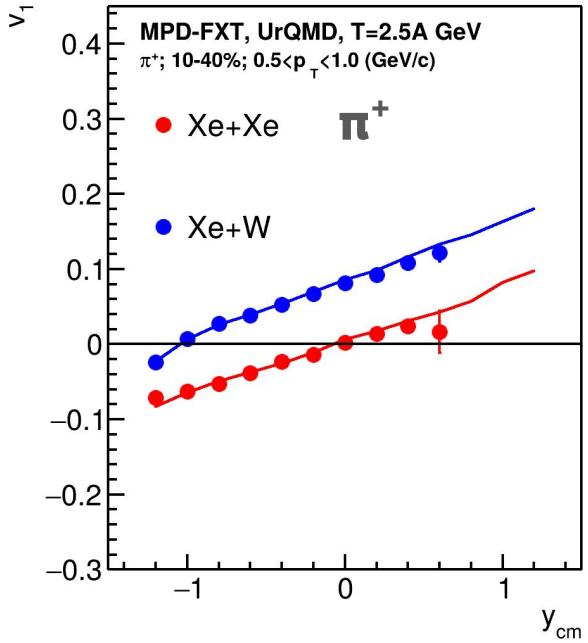


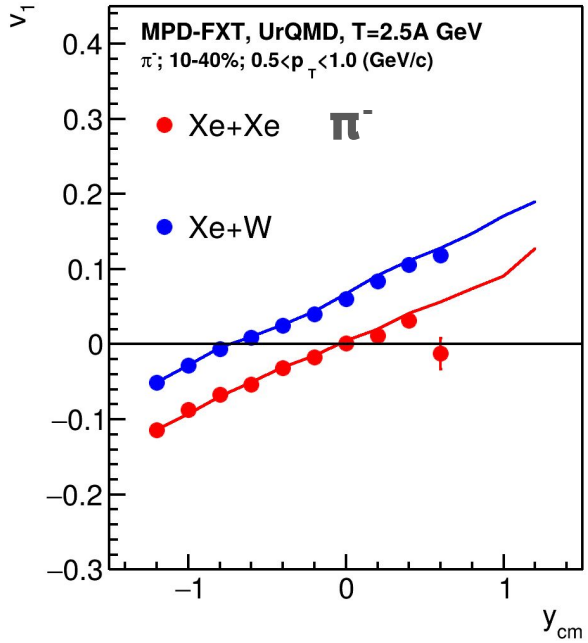
Flow performance: MPD-FXT

markers - reco; lines - model

Petr Parfenov et. al., Phys.Part.Nucl. 56 (2025) 3, 921-927
Petr Parfenov et. al., Int. J. Mod. Phys. E (2026) 2641021







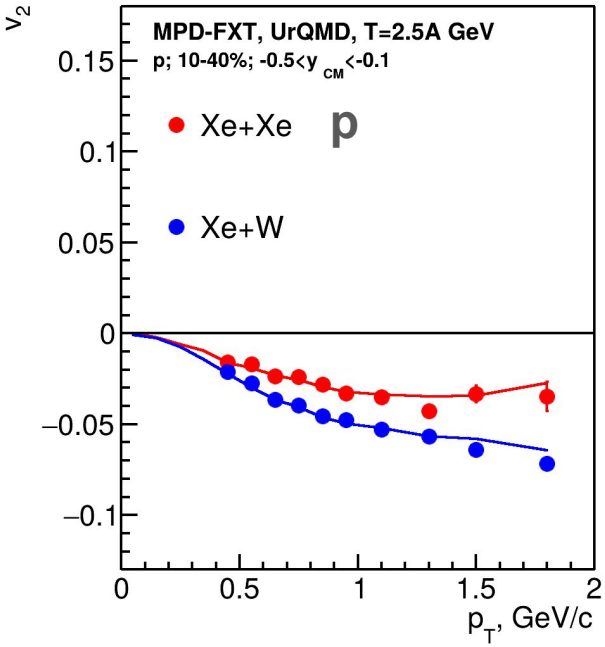
Good agreement for protons and pions for y<0.5

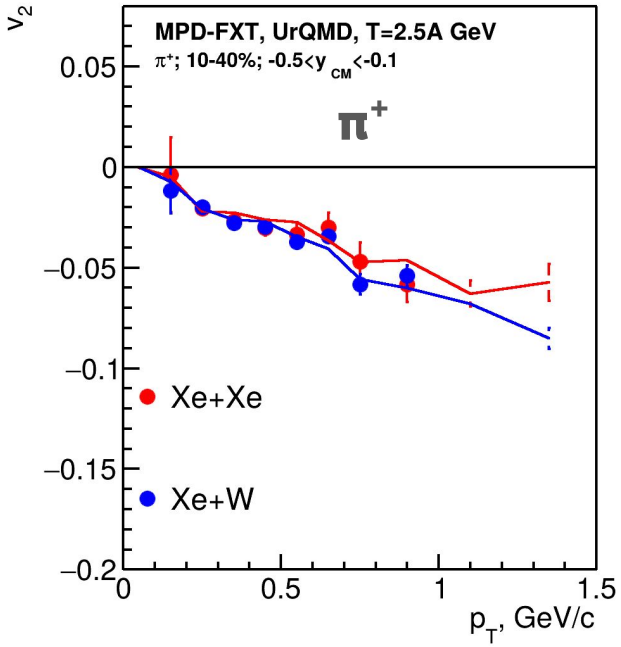
Clear shift in $v_1(y_{cm})$ for Xe+W - preferential deflection of the participants

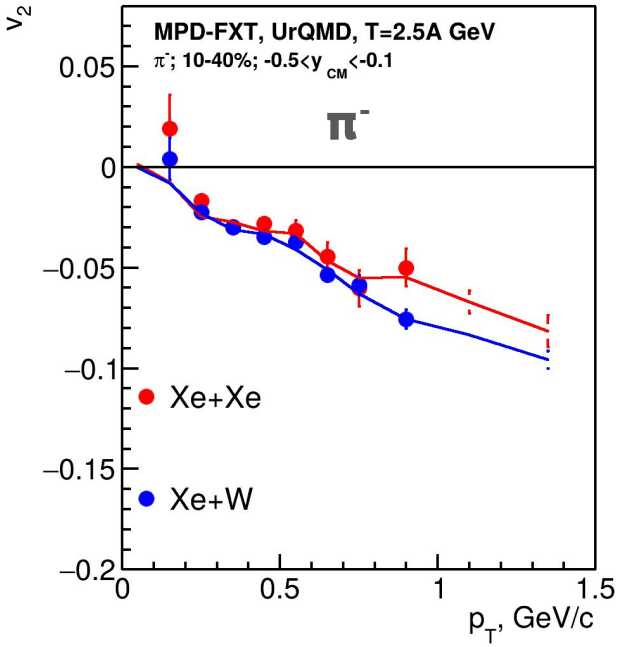
Flow performance: MPD-FXT

markers - reco; lines - model

Petr Parfenov et. al., Phys.Part.Nucl. 56 (2025) 3, 921-927
Petr Parfenov et. al., Int. J. Mod. Phys. E (2026) 2641021

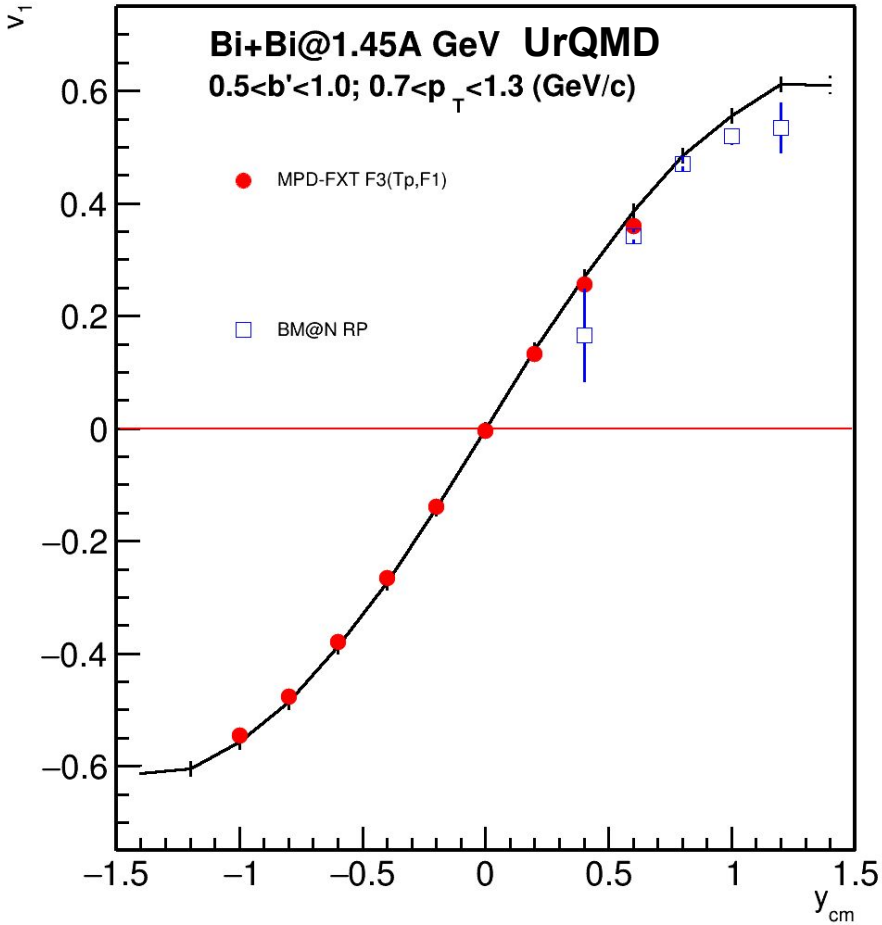






Good agreement for protons and pions

Comparison with the BM@N performance



Both MPD-FXT and BM@N can be used in v_n measurements:

- To widen rapidity coverage
- To perform a cross-check in the future

QnTools is also used in the v_n measurements in the BM@N experiment

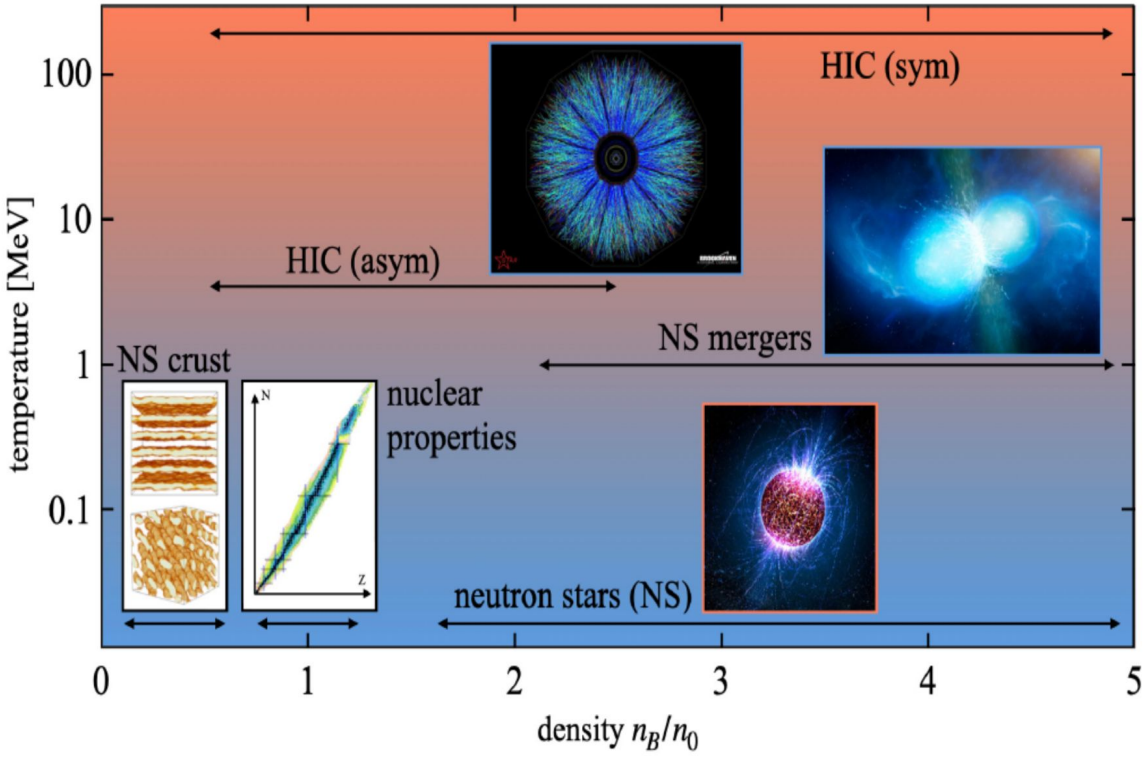
Заключение

1. Впервые разработаны и апробированы методы измерения эллиптических потоков v_2 адронов, позволяющих провести сравнительный анализ результатов экспериментальных данных и модельных расчетов в присутствии эффектов непотоковых корреляций и флуктуаций v_2.
    a. Методы определения центральности, основанные на MC-Glauber модели и обратной теореме Байеса воспроизводят геометрические параметры в классах центральности при тестировании на модельных данных
    b. Методы измерения v_2 успешно адаптированы в эксперименте MPD и апробированы в эксперименте STAR и с помощью ядро-ядерных моделей
2. Впервые проведен системный сравнительный анализ результатов измерений эллиптического потока v_2 протонов с теоретическими моделями в рассматриваемом энергетическом диапазоне.
3. Впервые были использованы модельные данные с полной реалистичной реконструкцией событий для оценок эффективности измерения v_2 адронов.

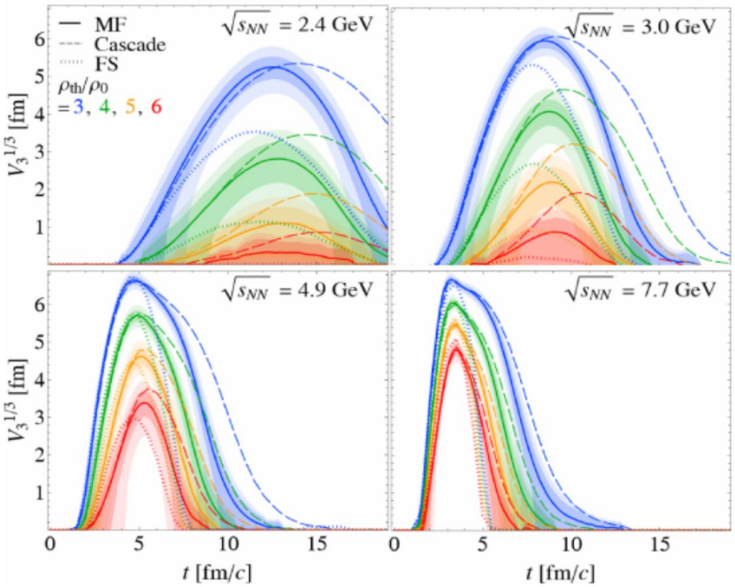
Спасибо за внимание!

Backup

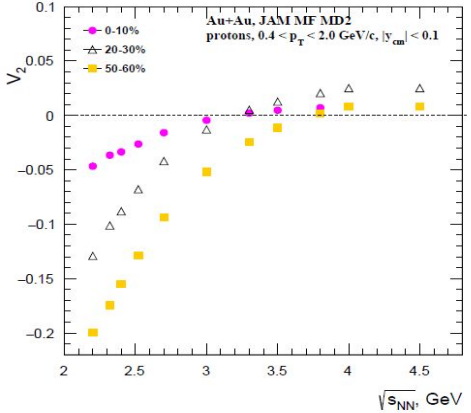
Compressed baryonic matter in the laboratory and astrophysics



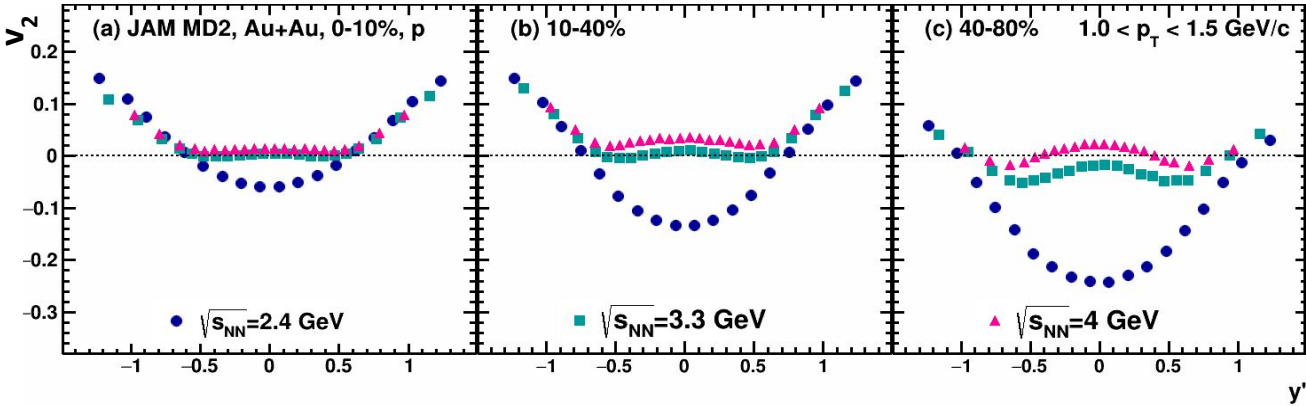
J.Subatomic Part.Cosmol. 3 (2025) 100015

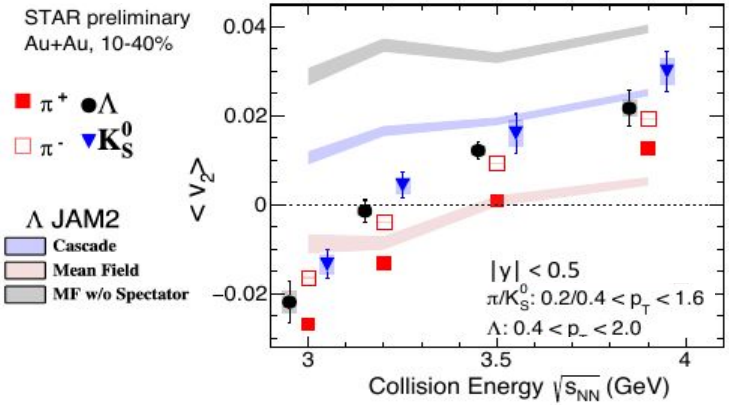


v_2 transition from out-of-plane to in-plane



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





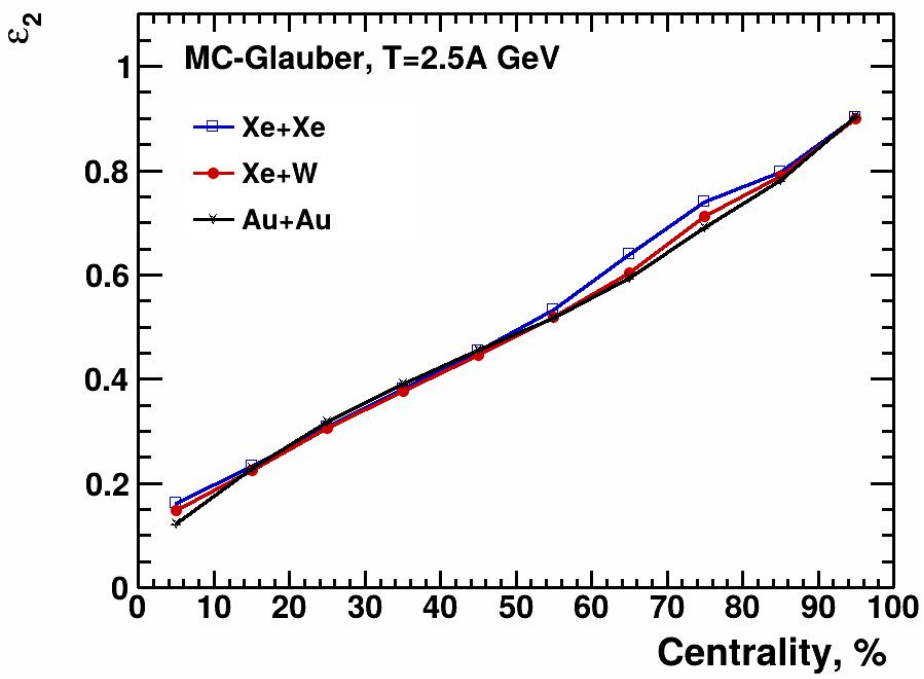
Transition of v_2 from out-of-plane to in-plane can be a good tool to constrain models and extract information about EOS

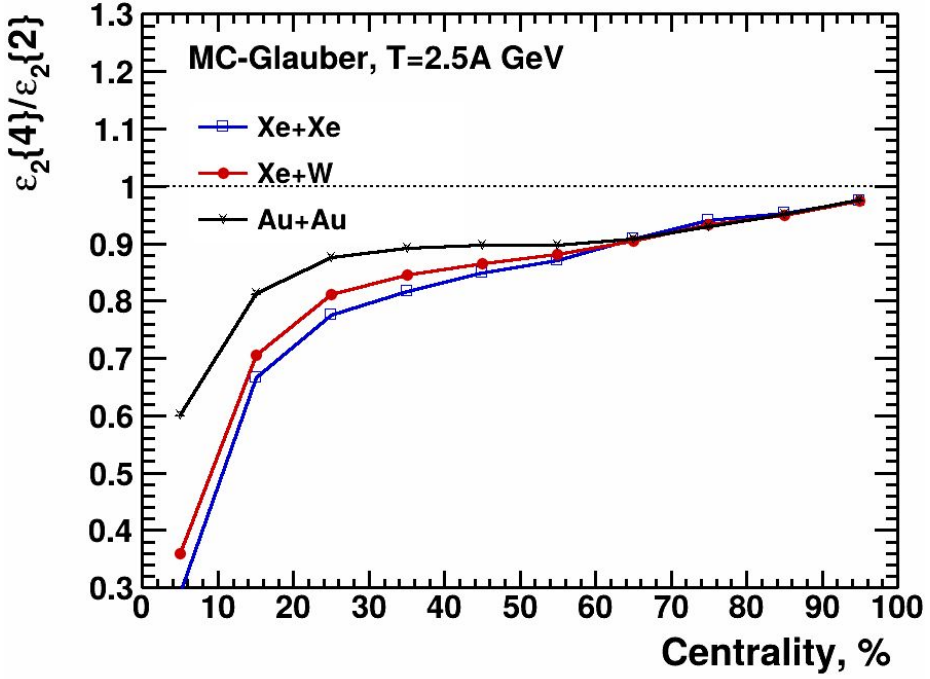
- $v_2 \approx 0$ in midrapidity at $\sqrt{s_{NN}}$=3.3 GeV for central and mid-central collisions for protons
- $v_2 < 0$ for peripheral collisions
- Models can not reproduce v_2 of $\pi^{\pm}$, $K^{\pm}$, K^0_S, Λ

Transition from out-of-plane to in-plane depends on centrality, rapidity and particle species

ε_2: scalable geometry, but different fluctuations! (centrality)

Petr Parfenov, Particles & Nuclei, 57 (2026)





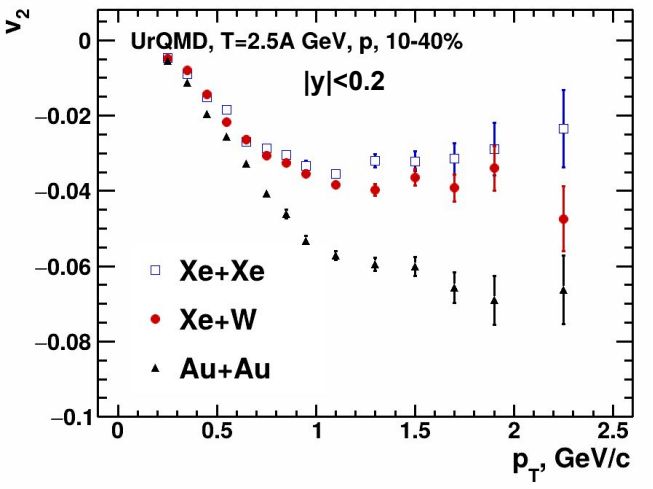
In central and mid-central collisions:

The overall geometry (ε_2) seems to scale with system size, but the fluctuations ($\varepsilon_2\{4\}/\varepsilon_2\{2\}$) are different between Xe+Xe, Xe+W and Au+Au

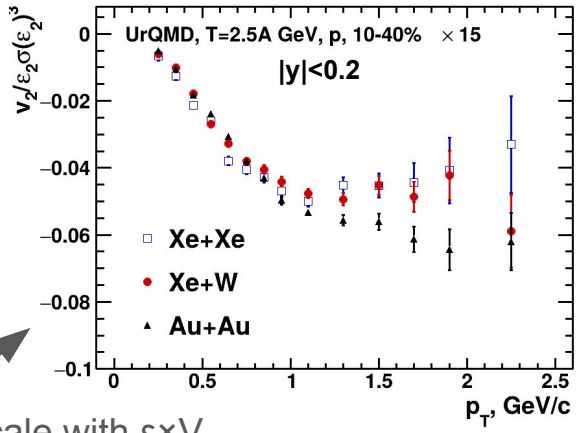
Testing for v_2 scaling in different collision systems

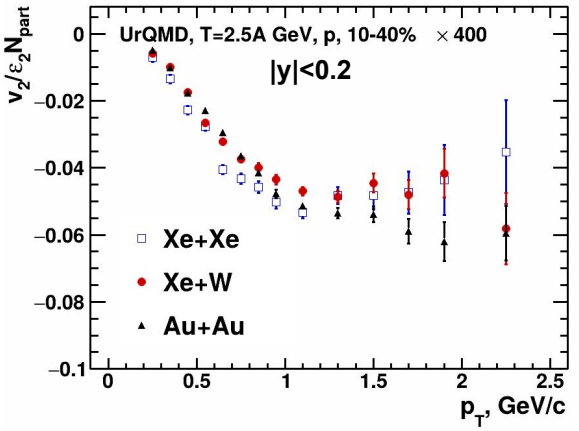
Petr Parfenov, Particles & Nuclei, 57 (2026)

$$\sigma(\varepsilon_2) = \frac{\varepsilon_2\{4\}}{\varepsilon_2\{2\}} = \frac{\sqrt[4]{|2\langle\varepsilon_2^2\rangle^2 - \langle\varepsilon_2^4\rangle|}}{\sqrt{\langle\varepsilon_2^2\rangle}}$$

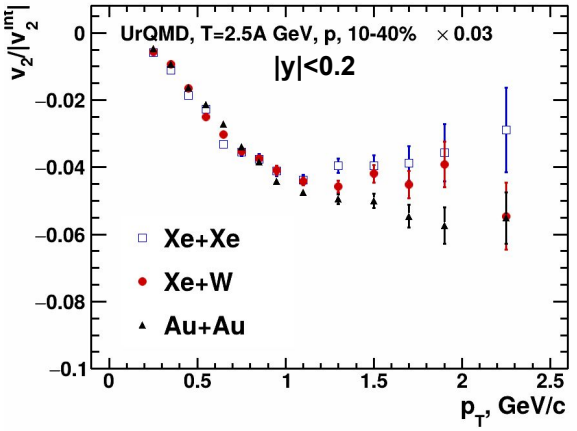


Scale with ε×V





Scale with v_2^{int}

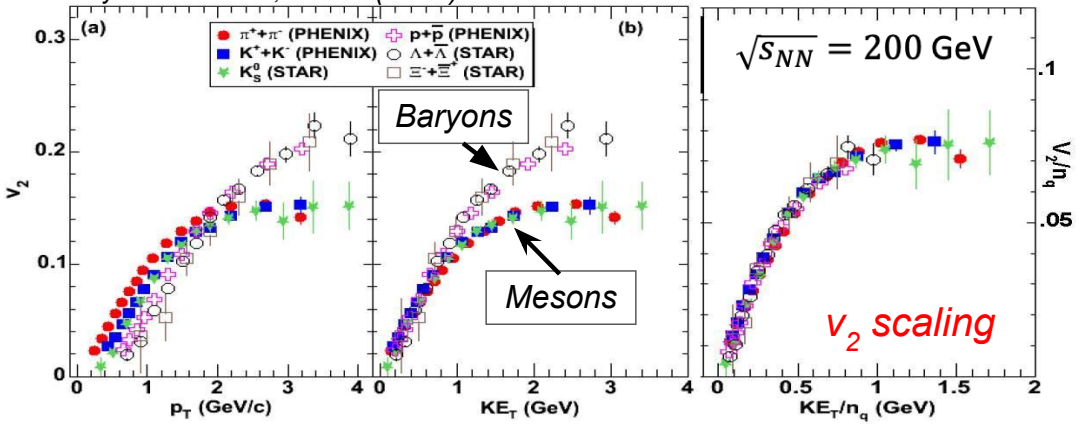


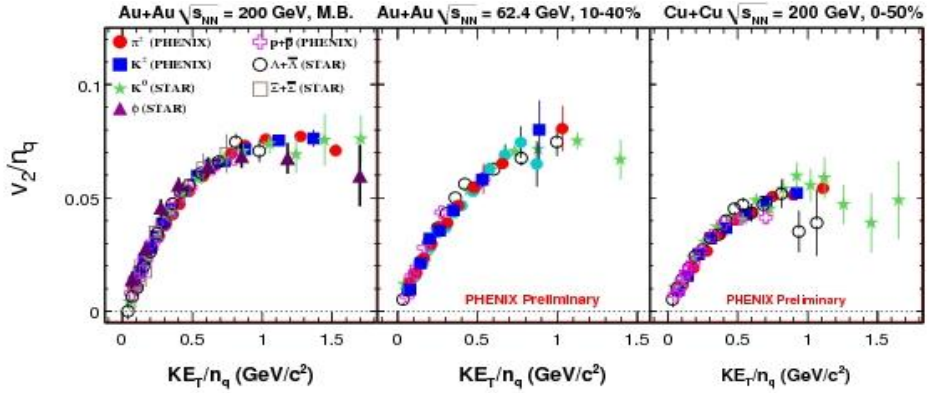
Scaling with v_2^{int} and ε×V can be applied (however they are weak)

Does v_n depend on the volume or just a coincidence?

Scaling relations at RHIC/LHC – NCQ (KE_T/n_q) scaling

Phys. Rev. Lett. 98, 162301 (2007)





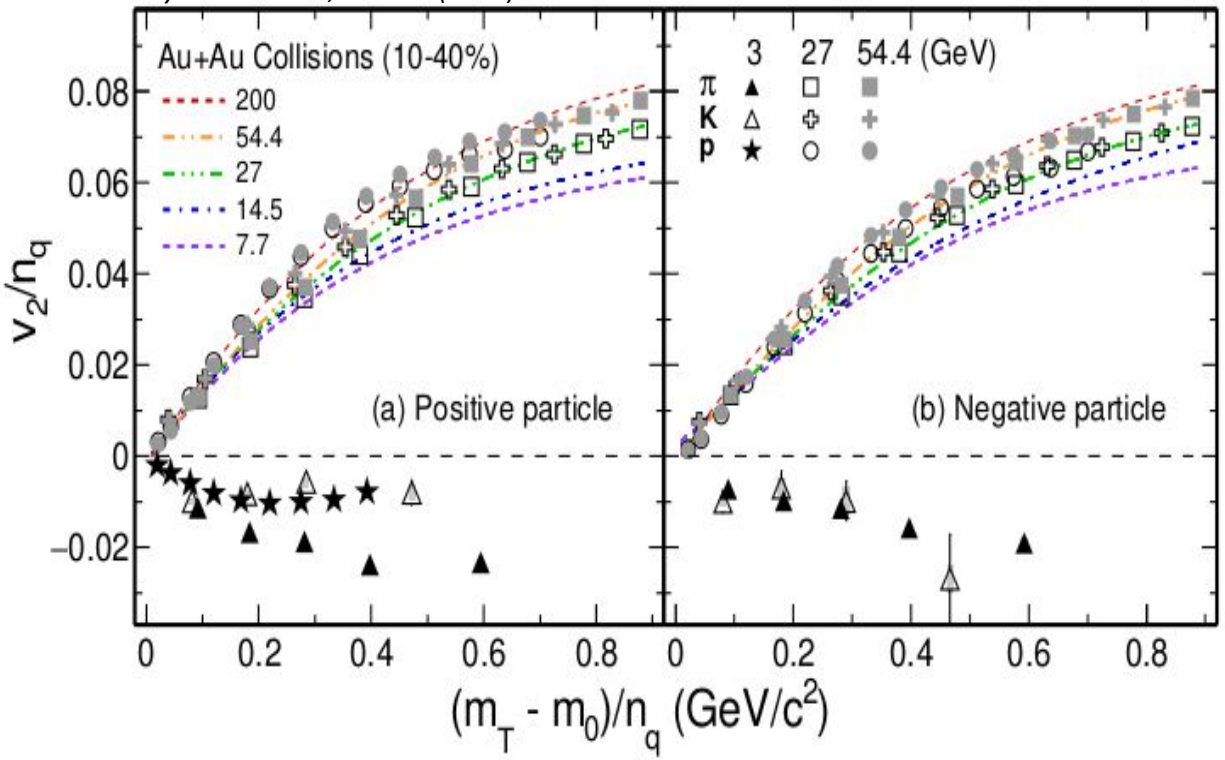
NCQ scaling: $v_n(p_T) \rightarrow v_n/n_q^{n/2}(KE_T/n_q)$

$$n_q = \begin{cases} 2 \text{ for mesons} \\ 3 \text{ for baryons'} \end{cases} \qquad KE_T = \sqrt{m^2 + p_T^2} - m$$

- Significant part of flow at RHIC developed at partonic level
- Scaling provides an additional constraint for the mechanism for hadronization at RHIC

Dissapearence of partonic collectivity in $\sqrt{s_{NN}} = 3$ GeV Au+Au collisions at RHIC

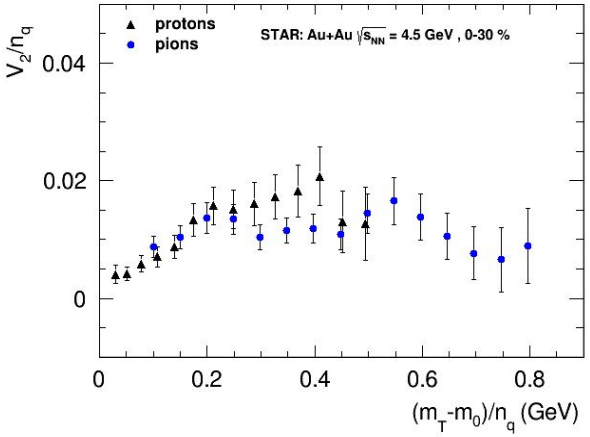
Phys. Lett. B 827, 137003 (2022)

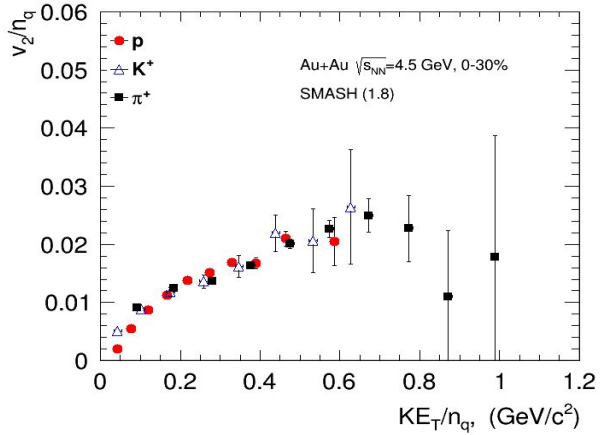


Breaking of NCQ scaling at 3 GeV

"imply the vanishing of partonic collectivity and a new EOS, likely dominated by baryonic interactions in the high baryon density region"

NCQ scaling: hybrid and cascade models

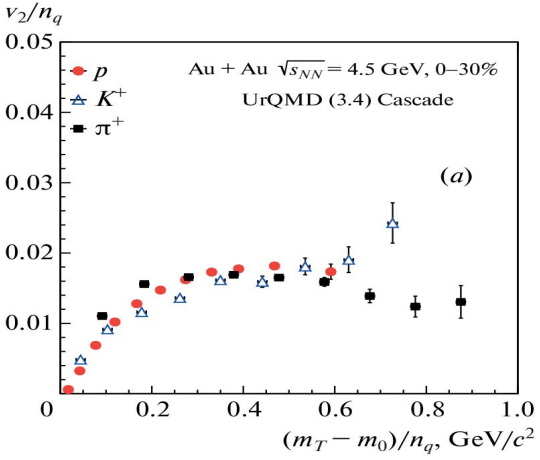


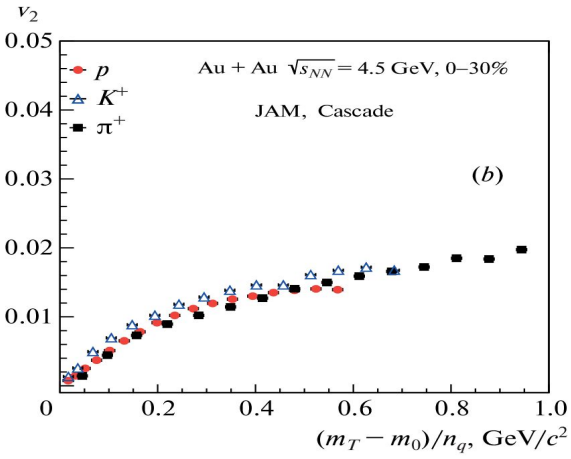


- Scaling holds up at 4.5 GeV in STAR data and pure string/hadronic cascade models (without partonic d.o.f.)

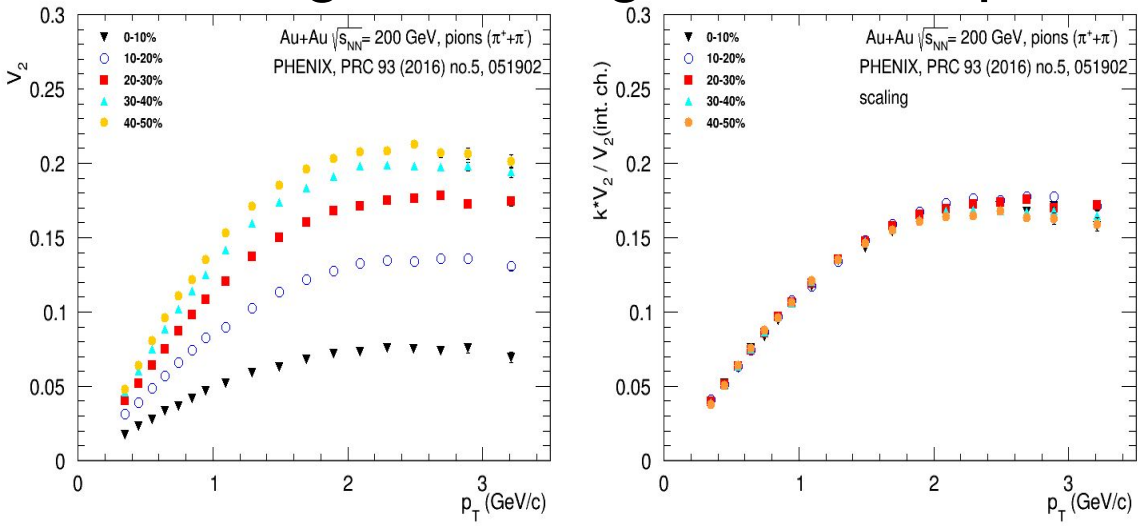
KE_T/n_q scaling at 4.5 GeV might be accidental – more careful studies should be performed

Petr Parfenov et. al., Phys.Part.Nucl.Lett. 20 (2023) 5, 1220-1223





Scaling with integral anisotropic flow

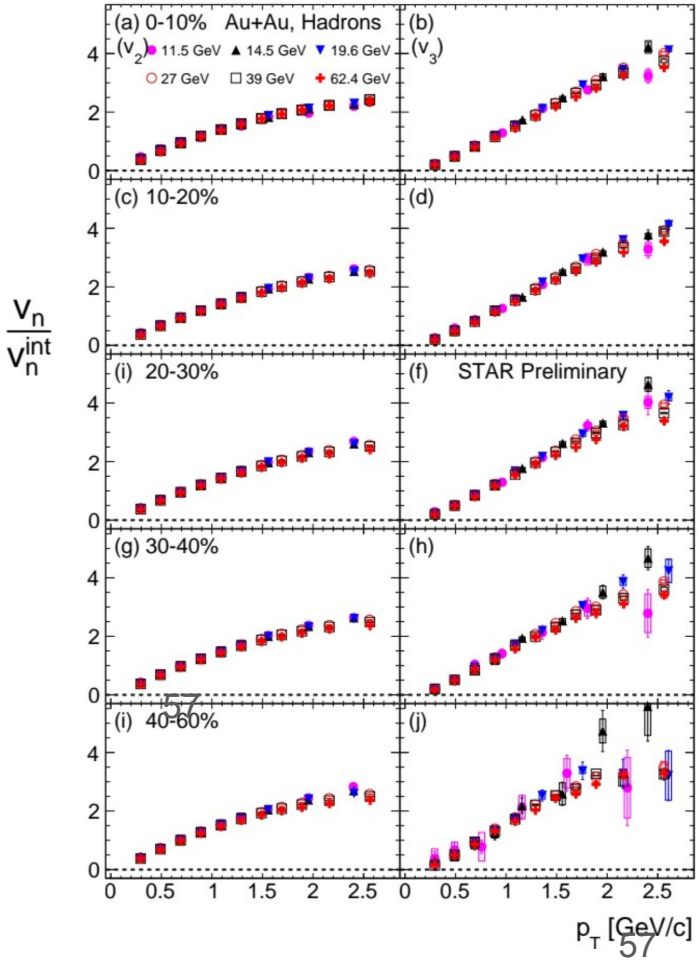


$$v_n(int.) \equiv \left|v_n^{int}\right| = \left|\langle v_n(p_T, y, \text{centrality, PID})\rangle_{p_T,y}\right|$$

Scaling works at top RHIC and BES energy range

Similar trend for pions, kaons and protons

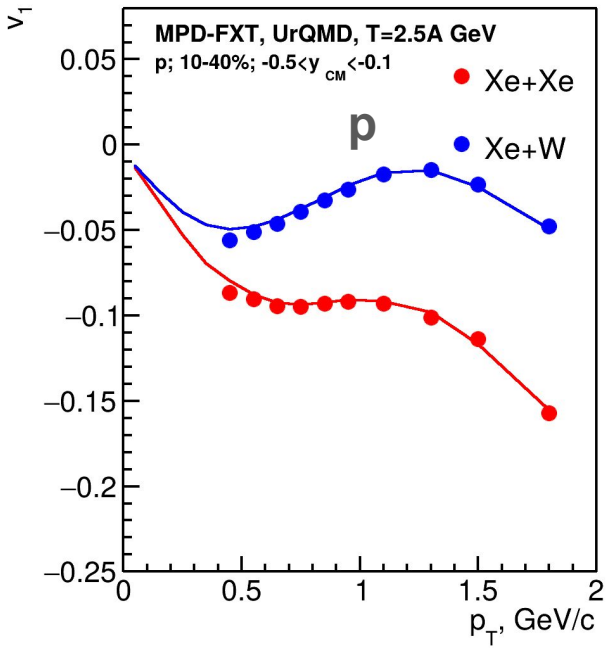
Petr Parfenov, *J.Phys.Conf.Ser.* 1690 (2020) 1, 012128

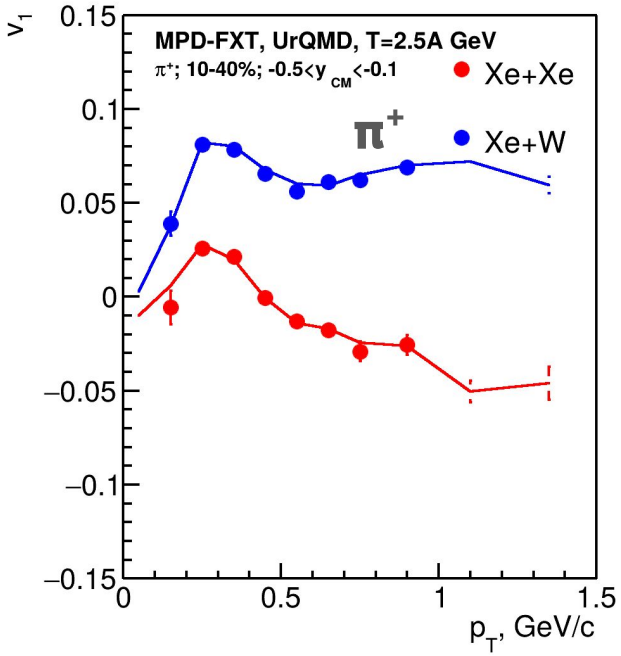


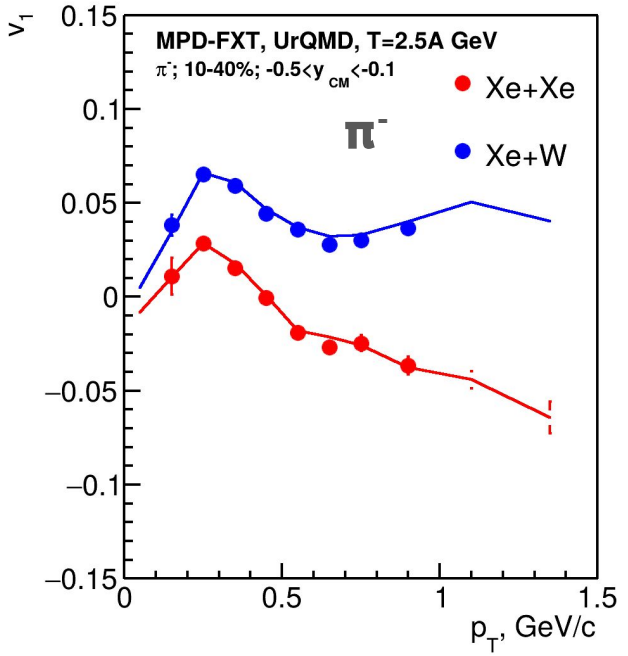
Flow performance: MPD-FXT

markers - reco; lines - model

Petr Parfenov et. al., Phys.Part.Nucl. 56 (2025) 3, 921-927
Petr Parfenov et. al., Int. J. Mod. Phys. E (2026) 2641021







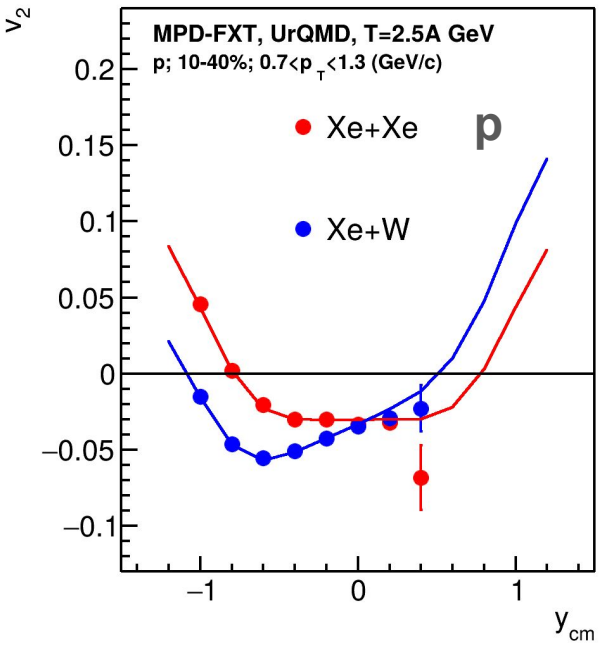
Good agreement for protons and pions for y<0.5

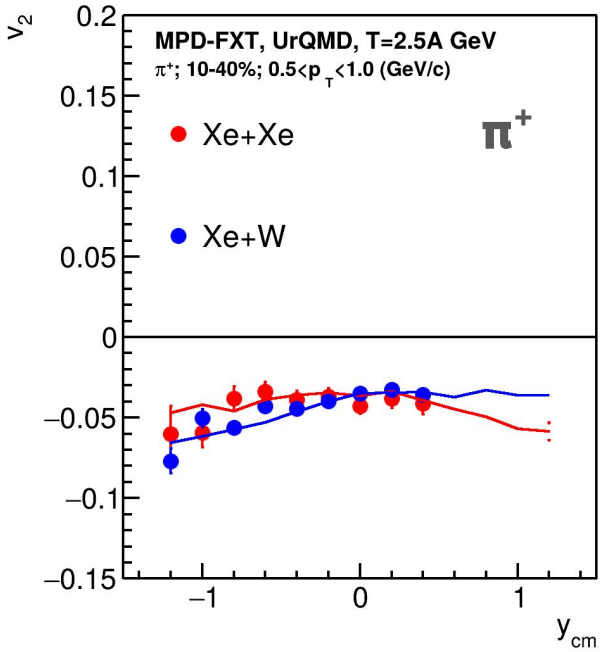
Clear shift in $v_1(y_{cm})$ for Xe+W - preferential deflection of the participants

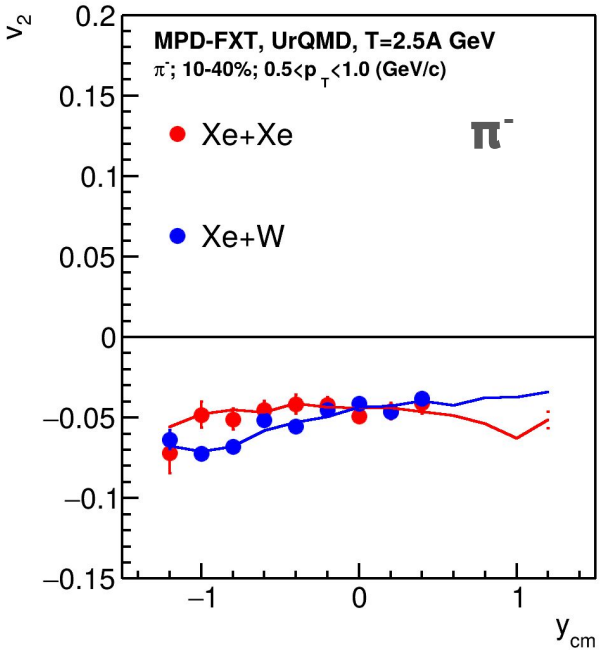
Flow performance: MPD-FXT

markers - reco; lines - model

Petr Parfenov et. al., Phys.Part.Nucl. 56 (2025) 3, 921-927
Petr Parfenov et. al., Int. J. Mod. Phys. E (2026) 2641021





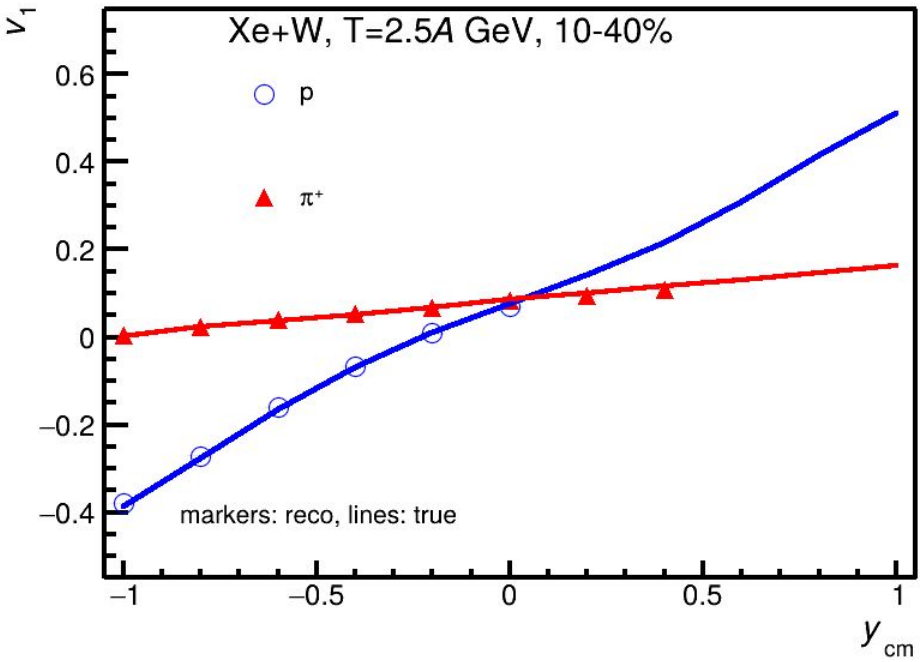


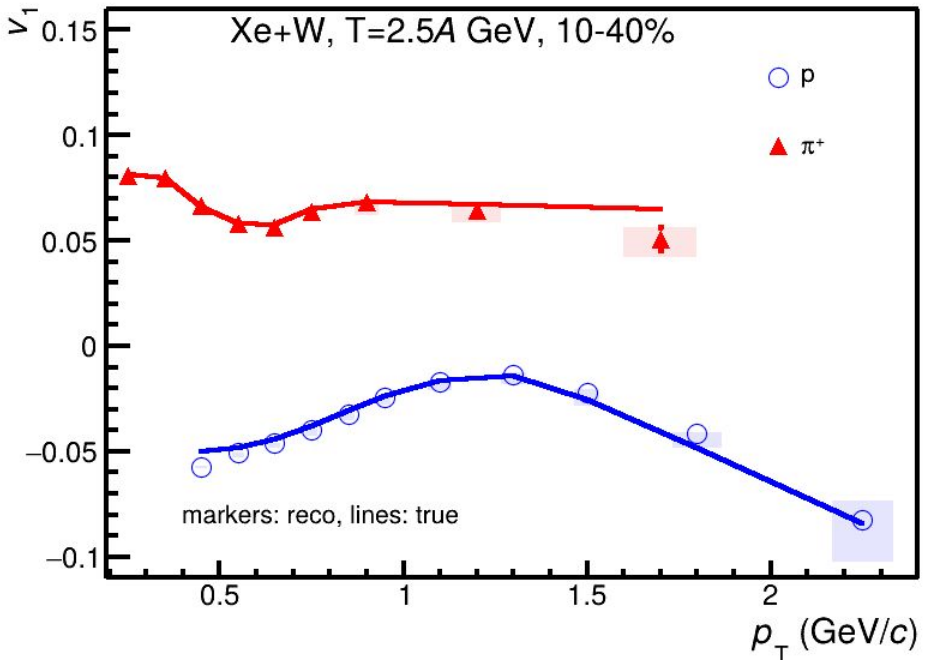
Good agreement for protons and pions

Flow performance: MPD-FXT

Filled boxes - systematics from symmetry planes (F1, F2, F3) and components (xx, yy)

Petr Parfenov et. al., Phys.Part.Nucl. 56 (2025) 3, 921-927
Petr Parfenov et. al., Int. J. Mod. Phys. E (2026) 2641021





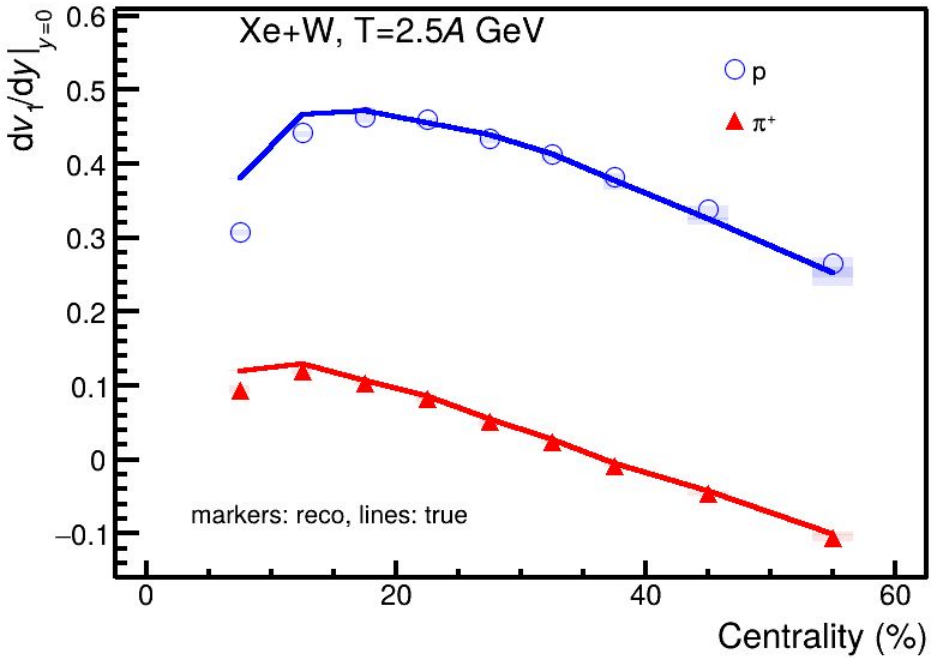
Good overall agreement between ‘true’ and ‘reco’ results

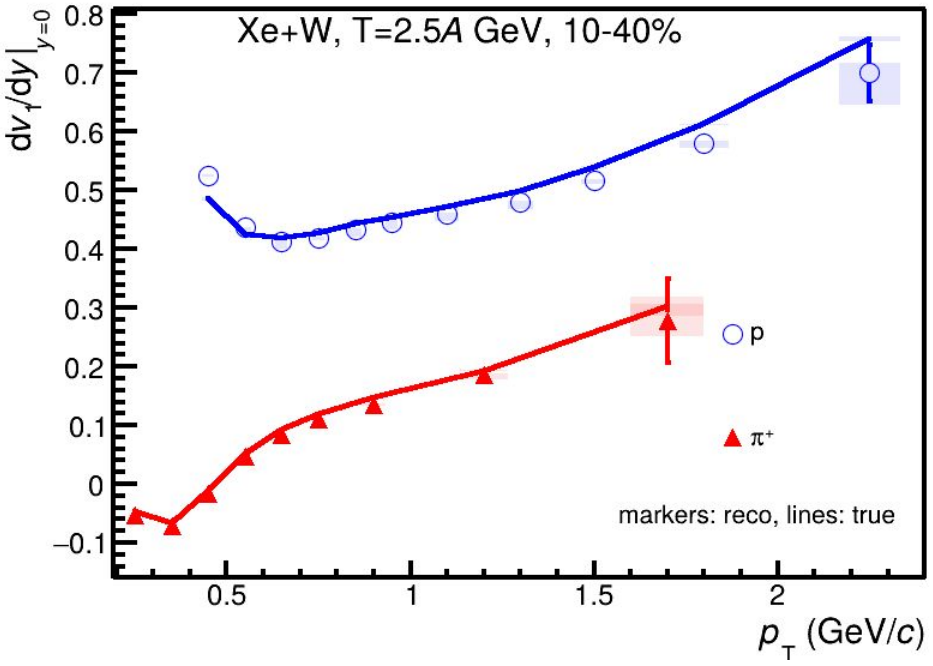
$v_1(y_{cm})$: (protons) $0.7<p_T<1.3$ GeV/c, (pions) $0.5<p_T<1.0$ GeV/c
$v_1(p_T)$: (protons, pions) $-0.5 < y_{cm} < -0.1$

Flow performance: MPD-FXT

Filled boxes - systematics from symmetry planes (F1, F2, F3) and components (xx, yy)

Petr Parfenov et. al., Phys.Part.Nucl. 56 (2025) 3, 921-927
Petr Parfenov et. al., Int. J. Mod. Phys. E (2026) 2641021





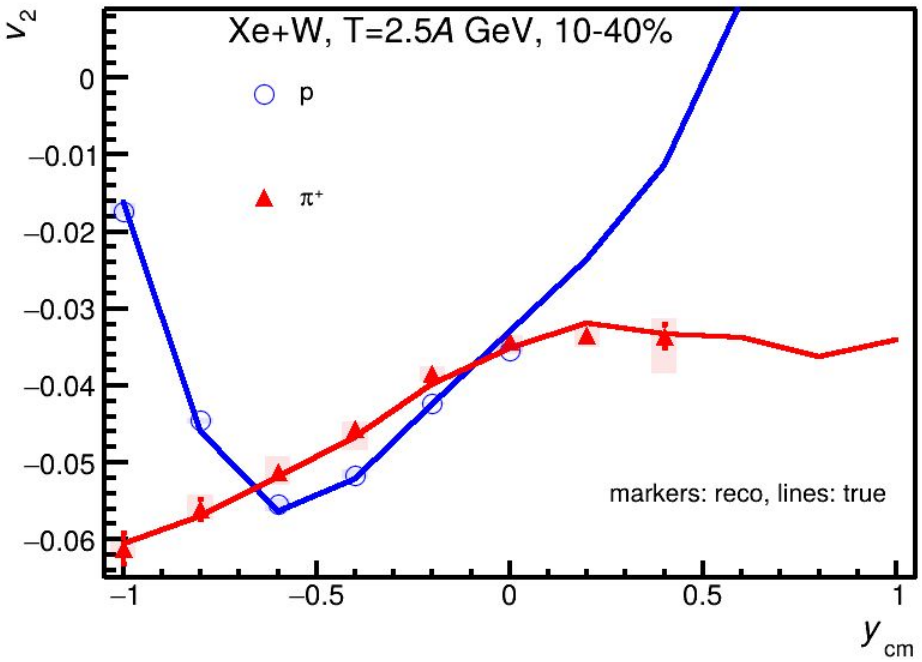
Good overall agreement between ‘true’ and ‘reco’ results

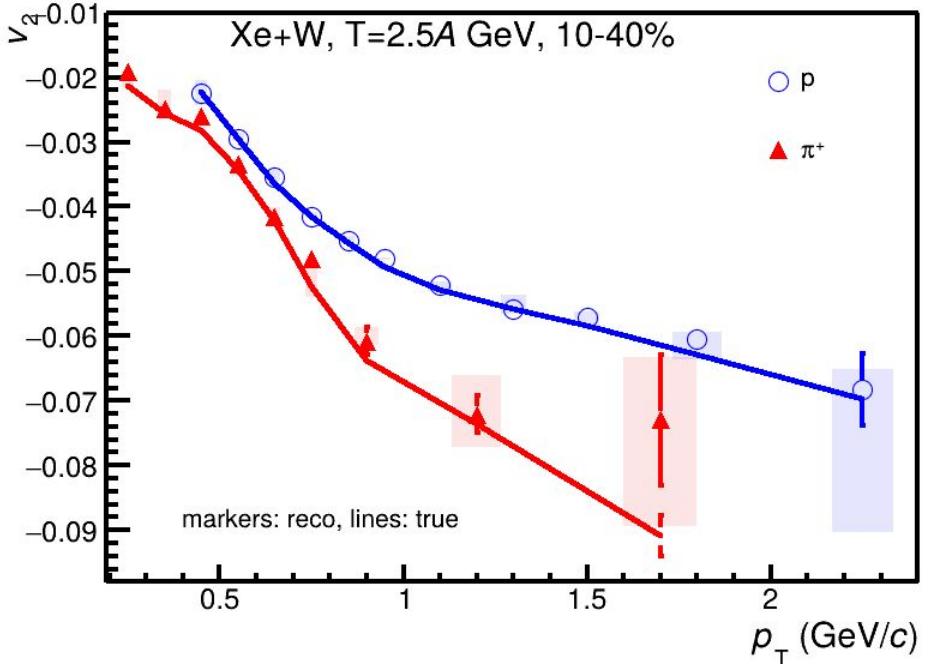
$v_1(y_{cm})$: (protons) $0.7<p_T<1.3$ GeV/c, (pions) $0.5<p_T<1.0$ GeV/c
$v_1(p_T)$: (protons, pions) $-0.5 < y_{cm} < -0.1$

Flow performance: MPD-FXT

Filled boxes - systematics from components (xxx, xyy, yyx, yxy)

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Petr Parfenov et. al., Int. J. Mod. Phys. E (2026) 2641021

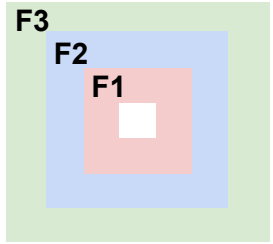




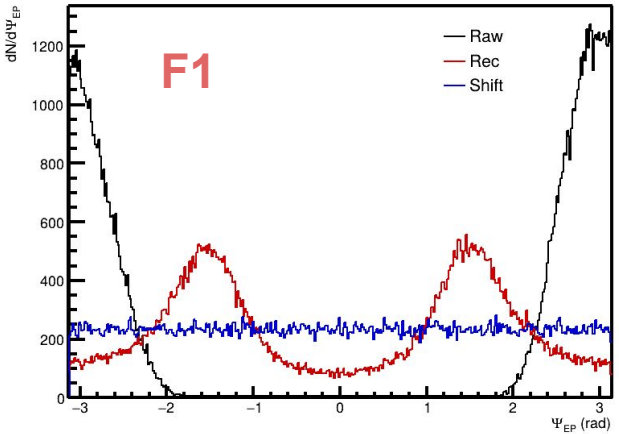
Good overall agreement between ‘true’ and ‘reco’ results

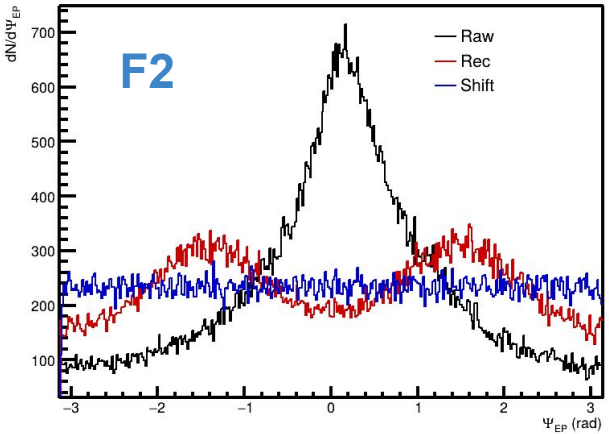
$v_2(y_{cm})$: (protons) $0.7<p_T<1.3$ GeV/c, (pions) $0.5<p_T<1.0$ GeV/c
$v_2(p_T)$: (protons, pions) $-0.5 < y_{cm} < -0.1$

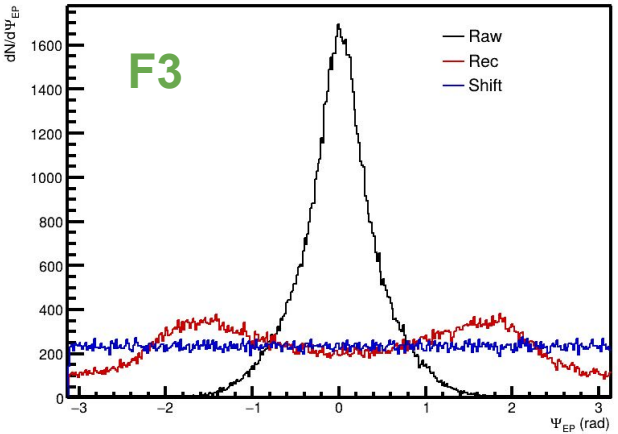
Event plane distributions (evPlaneFXT wagon)



Test data sample: 100k events







Ψ_{EP} distributions look reasonable at each step of the correction

EoS for high baryon density matter

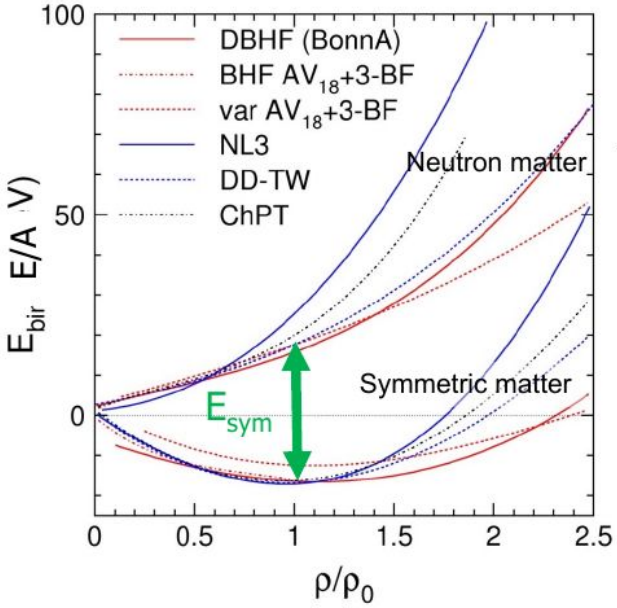
The binding energy per nucleon: $E_A(\rho,\delta) \propto E_A(\rho,0) + E_{sym}(\rho)\delta^2 + O(\delta^4)$

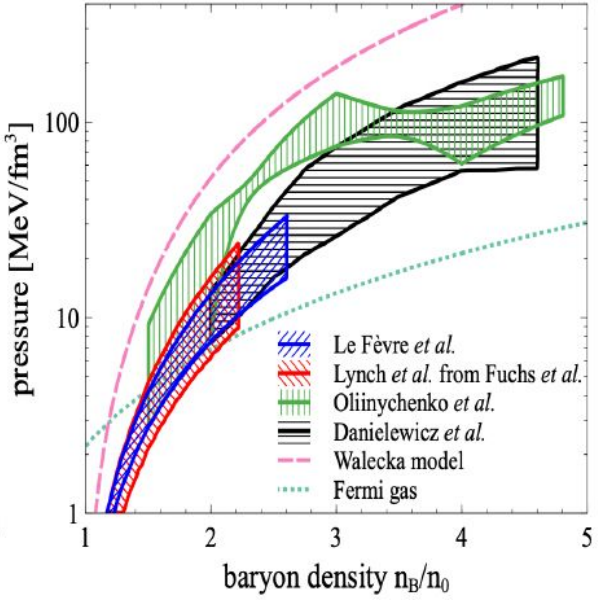
Isospin asymmetry: $\delta = (\rho_n - \rho_p)/\rho$

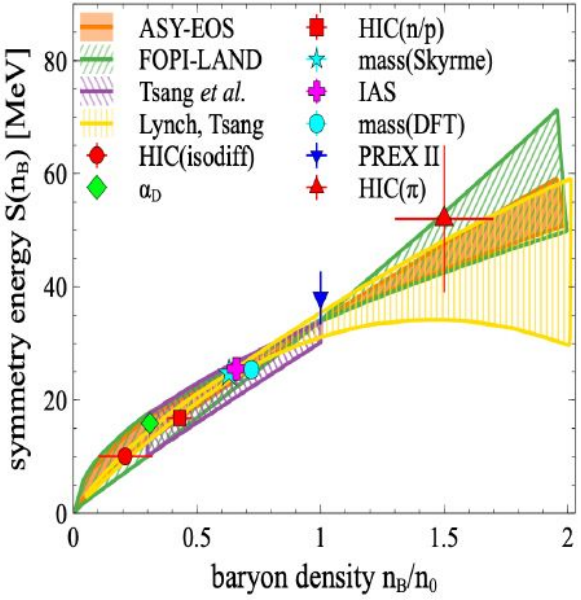
$P \propto \rho^2 \frac{dE_A}{d\rho}$

Symmetric matter

Symmetry energy







Ch. Fuchs and H.H. Wolter, EPJA 30 (2006) 5

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

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

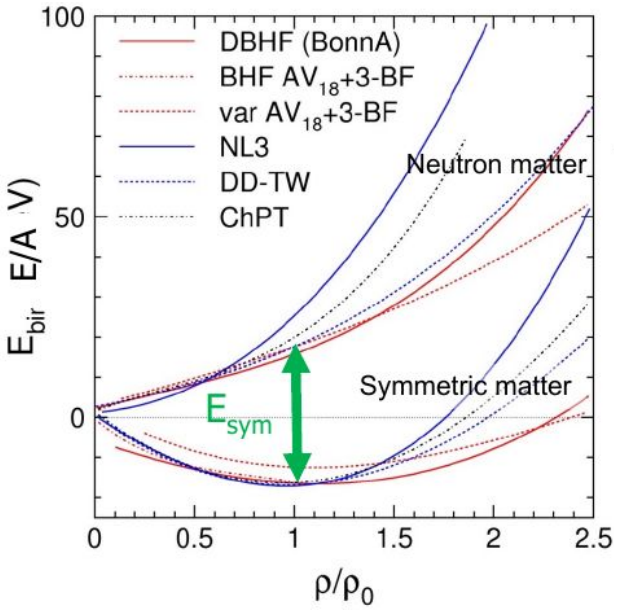
EoS for high baryon density matter

The binding energy per nucleon:

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

Isospin asymmetry:

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



Ch. Fuchs and H.H. Wolter, EPJA 30 (2006) 5

Symmetric matter

- Being extensively studied nowadays
- Using observables (flow, meson yields, etc.) to find incompressibility $\boldsymbol{K_0}$
- One of the main sources of uncertainty: discrepancy between experimental data

$$K_0 = 9\rho^2 \frac{\partial^2 E_A}{\partial \rho^2}$$

Symmetry energy

- No experimental data for beam energies $\sqrt{s_{NN}}$ >0.8 GeV
- One of the main parameter to study is the E_{sym} slope $\boldsymbol{L}$
- One needs to establish observables sensitive to $\boldsymbol{L}$ and obtain new experimental data

$$L = 3\rho \frac{\mathrm{d}E_{sym}}{\mathrm{d}\rho}$$

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

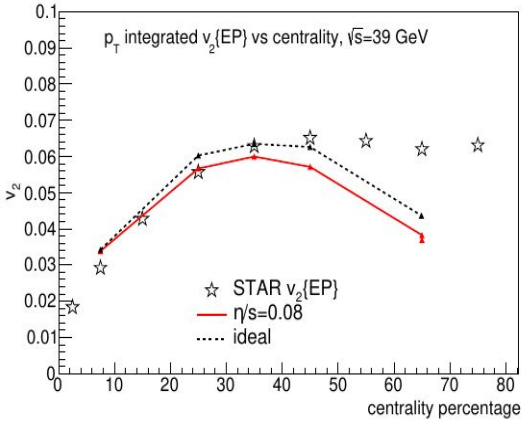
New data is needed to further constrain transport models with hadronic d.o.f.

Hybrid models for anisotropic flow at RHIC/LHC

1. UrQMD + 3D viscous hydro model vHLLE+UrQMD

Iurii Karpenko, Comput. Phys. Commun. 185 (2014), 3016
https://github.com/yukarpenko/vhlle
Parameters: from Iu. A. Karpenko, P. Huovinen, H. Petersen, M. Bleicher, Phys. Rev. C91 (2015) no.6, 064901 – good description of STAR BES results for v_2 of inclusive charged hadrons (7.7-62.4 GeV)

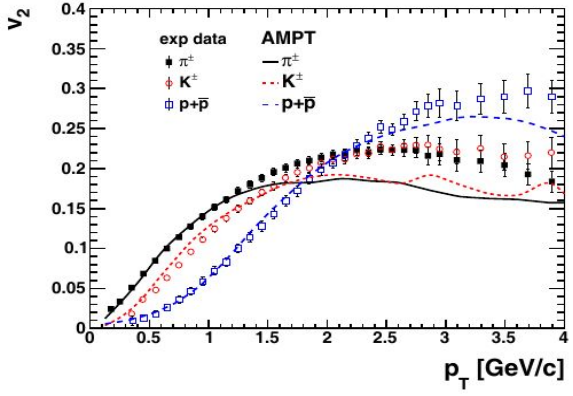
Initial conditions: model UrQMD
QGP phase: 3D viscous hydro (vHLLE) with crossover EOS (XPT)
Hadronic phase: model UrQMD



2. A Multi-Phase Transport model (AMPT) for high-energy nuclear collisions

The main source code (Zi-Wei Lin):
https://myweb.ecu.edu/linz/ampt/v1.26t9b/v2.26t9b

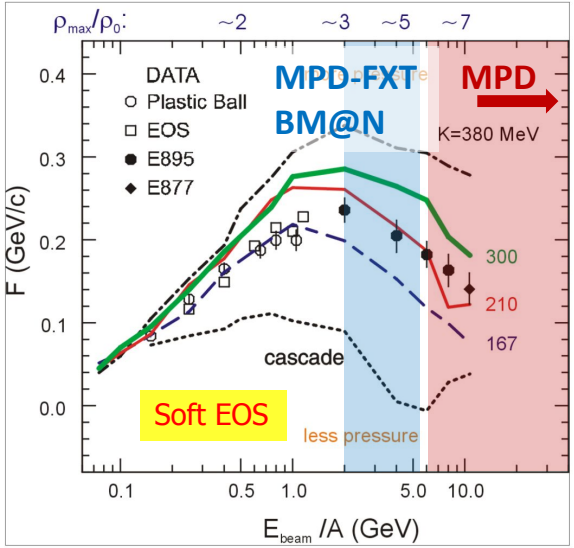
Initial conditions: model HIJING
QGP phase: Zhang's parton cascade for modeling partonic scatterings
Hadronic phase: model ART

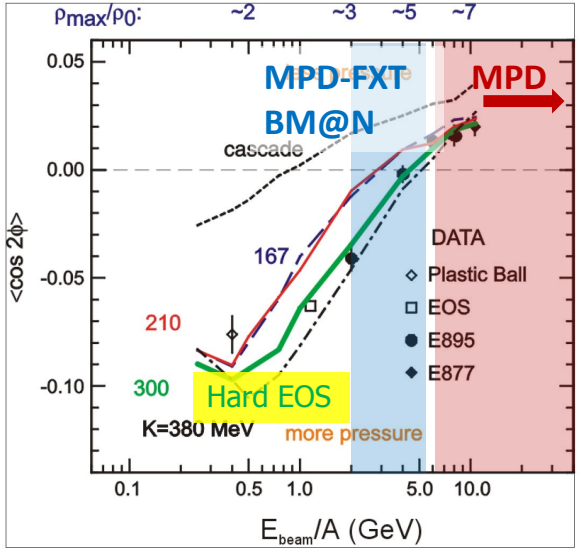


Z.W. Lin, C. M. Ko, B.A. Li, B. Zhang and S. Pal:
Physical Review C 72, 064901 (2005).

Sensitivity of the anisotropic flow to the EOS

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





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

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

Anisotropic flow sensitive to the EoS

EoS extraction: define incompressibility

$$K_0 = 9\rho^2 \frac{\partial^2(E_A)}{\partial \rho^2}$$

Discrepancy in the interpretation:

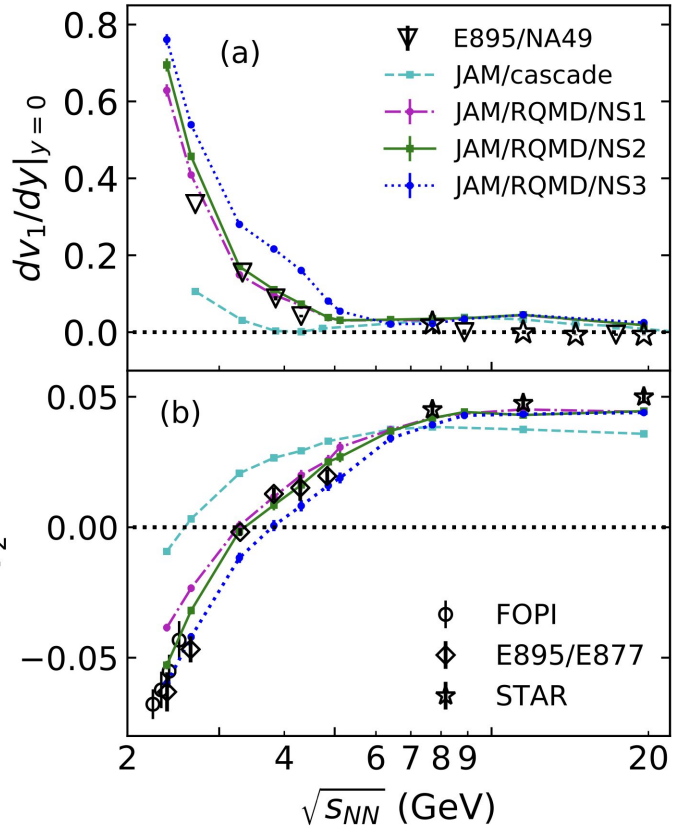
- v_1 suggests soft EoS (K_0≈210 MeV)
- v_2 suggests hard EoS (K_0≈380 MeV)

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

Additional measurements are essential to clarify the previous results

Anisotropic flow study at $\sqrt{s_{NN}}$=2-4 GeV with JAM model

Y.Nara, et al., Phys. Rev. C 100, 054902 (2019)



To study energy dependence of v_n, JAM microscopic model was selected (ver. 1.90597)

NN collisions are simulated by:

- $\sqrt{s_{NN}}$<4 GeV: resonance production
- 4<$\sqrt{s_{NN}}$<50 GeV: soft string excitations
- $\sqrt{s_{NN}}$>10 GeV: minijet production

We use RQMD with relativistic mean-field theory (non-linear σ-ω model) implemented in JAM model

Different EOS were used:

- **MD2** (momentum-dependent potential): K=380 MeV, m^*/m=0.65, $U_{opt}(\infty)$=30
- **MD4** (momentum-dependent potential): K=210 MeV, m^*/m=0.83, $U_{opt}(\infty)$=67
- **NS1**: K=380 MeV, m^*/m=0.83, $U_{opt}(\infty)$=95
- **NS2**: K=210 MeV, m^*/m=0.83, $U_{opt}(\infty)$=98

Y.Nara, T.Maruyama, H.Stoecker Phys. Rev. C 102, 024913 (2020)

Y.Nara, H.Stoecker Phys. Rev. C 100, 054902 (2019)

Scaling properties of collective flow

"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 :

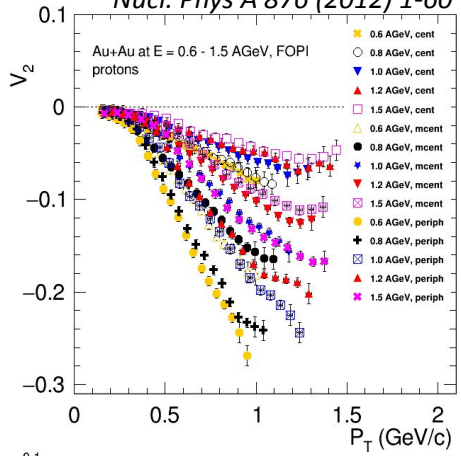
There is interest in using observables that are both coalescence and scale-invariant. …The evolution in non-viscous hydrodynamics does not depend on the size of the system nor on the incident energy, if distances are rescaled in terms of a typical size parameter, such as the nuclear radius. Momenta and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

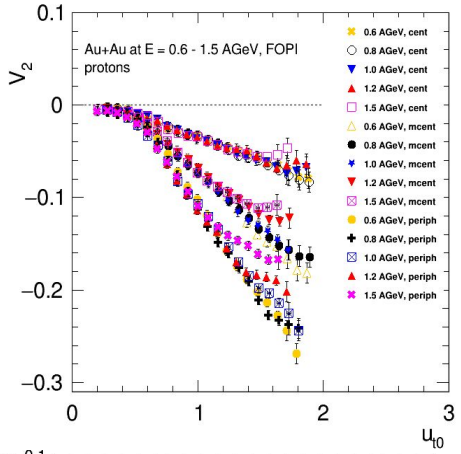
The idea to look for scaling relations and use them was proposed a long time ago

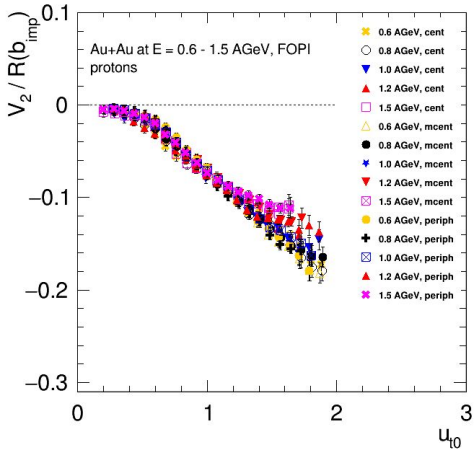
$$v_n(\sqrt{s_{NN}}, R, \text{centrality}, \text{PID}, p_T, y) = v_n(\sqrt{s_{NN}}, R, \text{centrality}) \times v_n(\text{PID}, p_T, y) \ ?$$

Scaling relations at SIS – scaling with passage time

Nucl. Phys A 876 (2012) 1-60

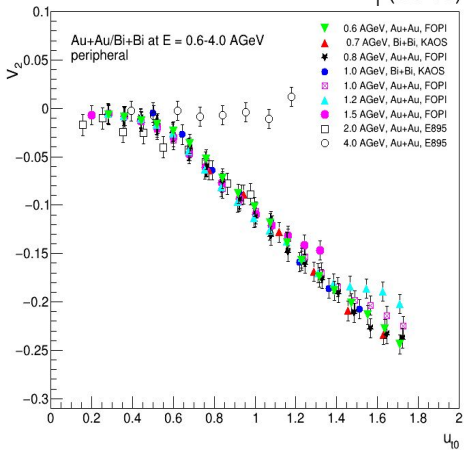


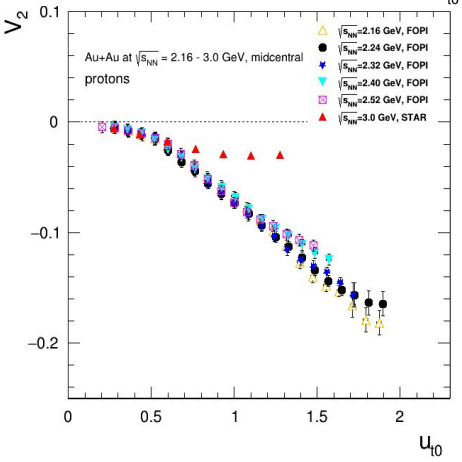




$$u_{t0} = \frac{p_T}{m_0 \beta_{CM} \gamma_{CM}} \equiv \frac{p_T t_{pass}}{2 R m_0}$$

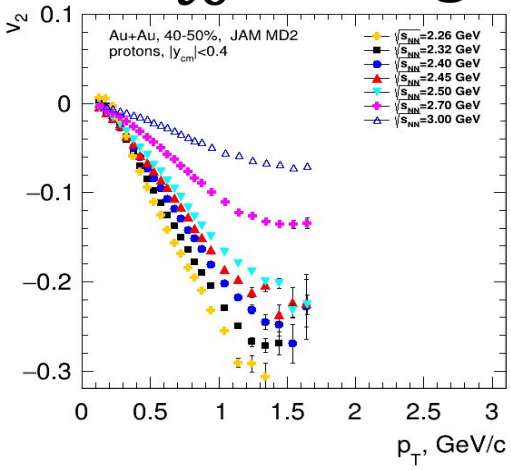
$$t_{pass} = \frac{2R}{\beta_{CM} \gamma_{CM}}$$

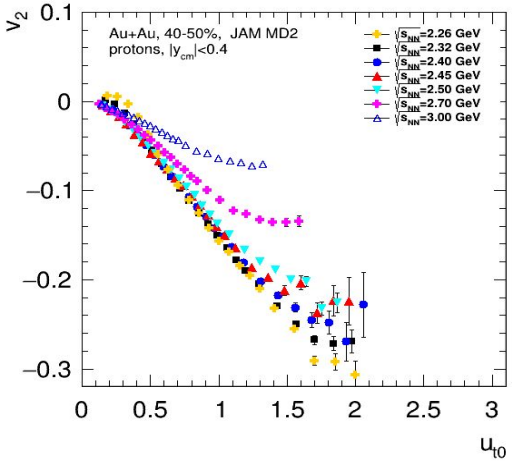


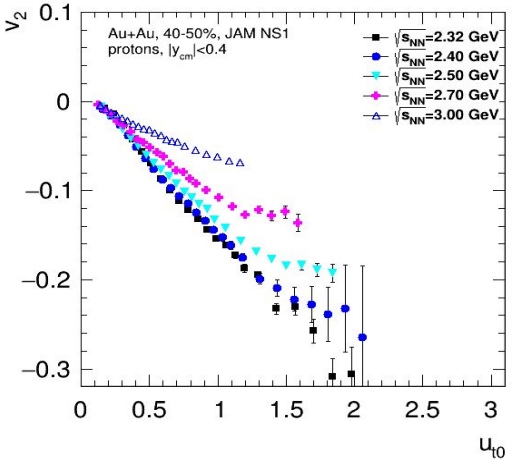


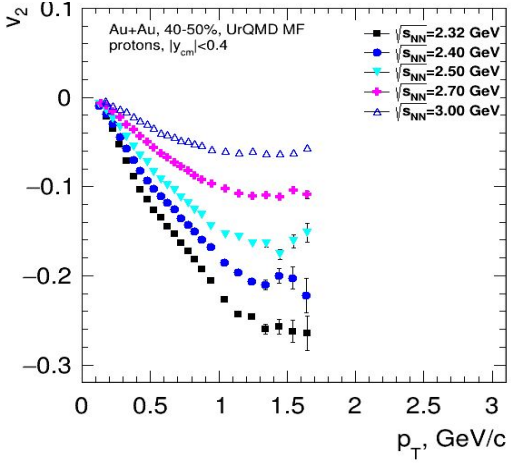
- The rather good scaling observed suggests that c_s does not change significantly over beam energy range $E_{kin} = 0.4 - 2$ AGeV ($\sqrt{s_{NN}} = 2 - 2.7$ GeV)
- Scaling breaks at $E_{kin} = 2.9$ AGeV ($\sqrt{s_{NN}} = 3$ GeV)

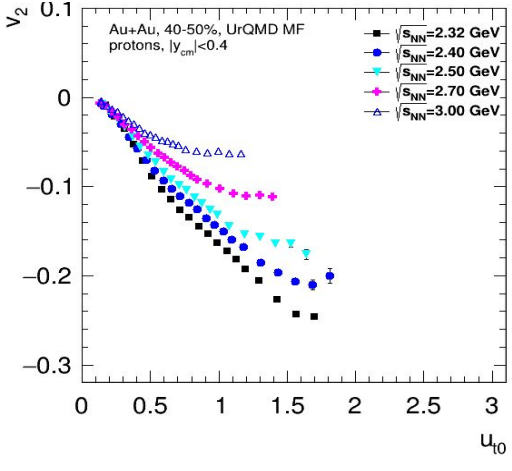
u_{t0} scaling: mean-field models





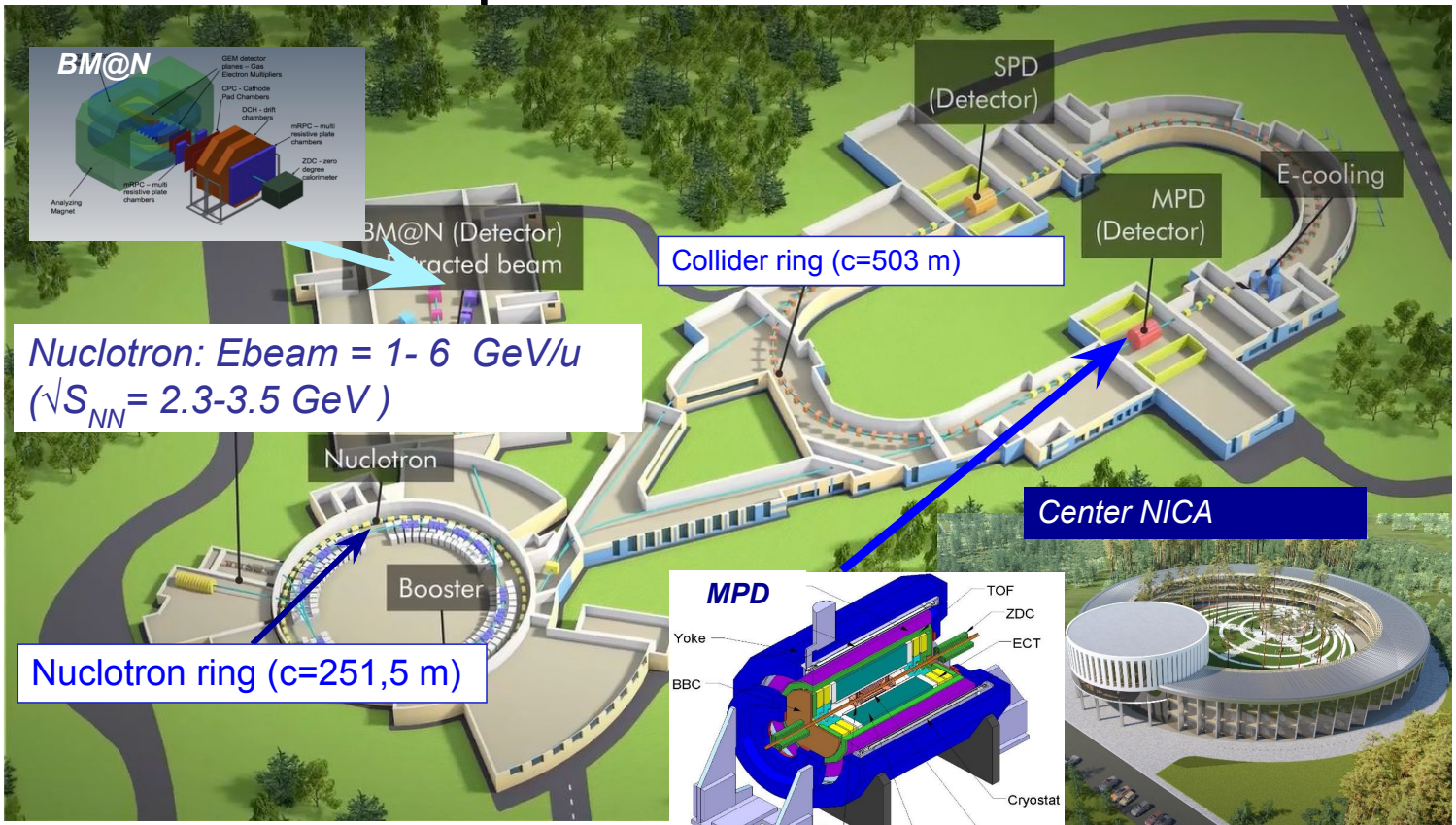






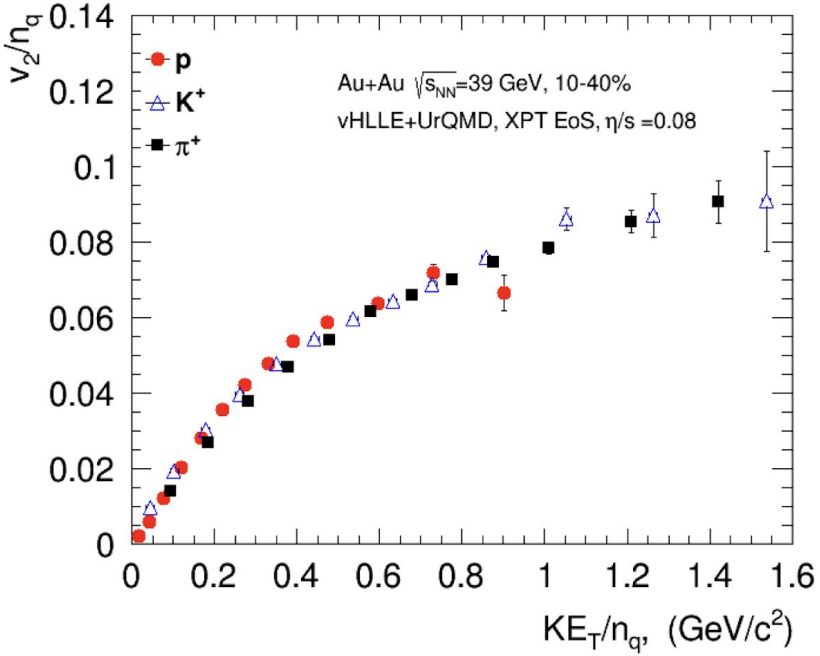
- Scaling holds for both JAM and UrQMD models with mean-field potentials for all EOS
- Similar trend with experimental data: scaling breaks at around $\sqrt{s_{NN}} \geq 2.7$ GeV
- Scaling can provide additional constraints for models

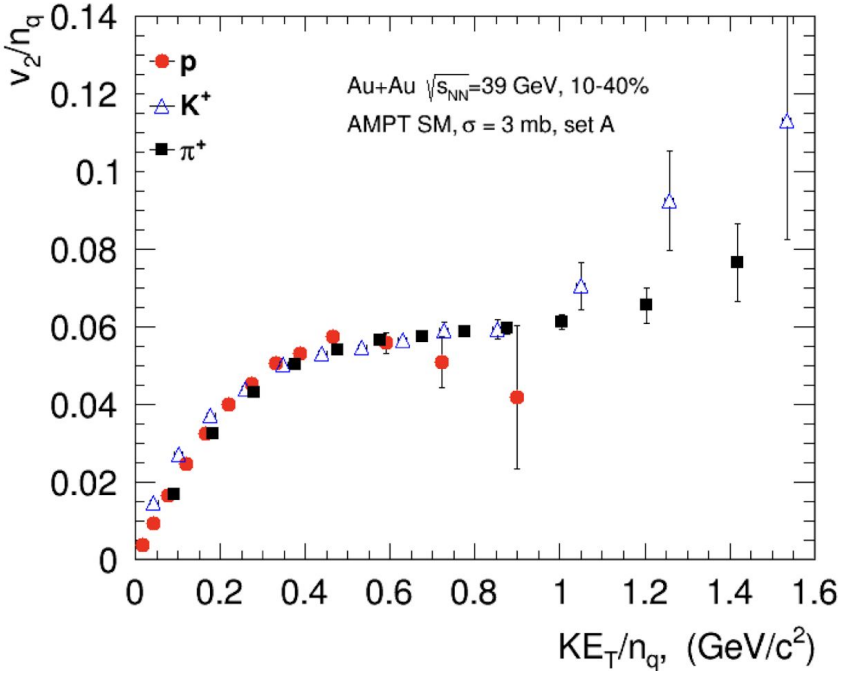
Accelerator complex NICA



NICA: $\sqrt{S_{NN}}$= 4-**11** GeV (Au^{79+})

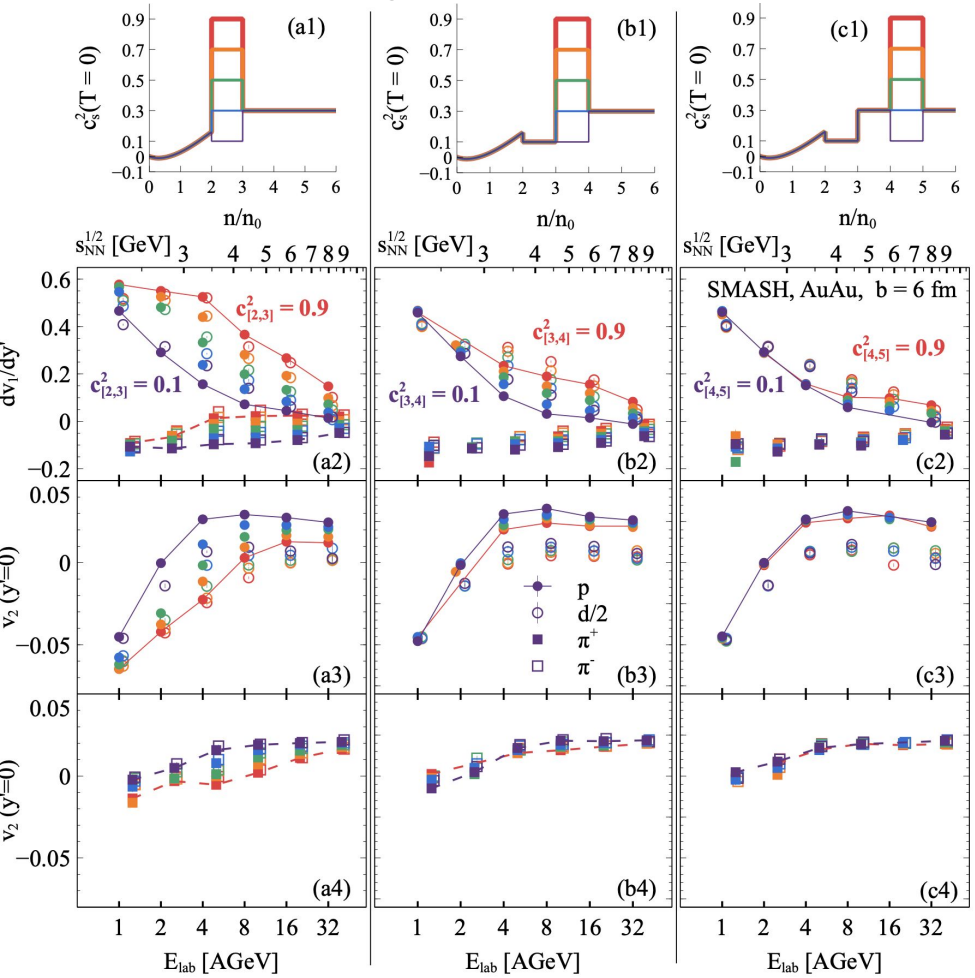
NCQ scaling: hybrid models





- Hybrid models with QGP phase are used for BES energy range ($\sqrt{s_{NN}} = 7.7 - 200$ GeV), such as vHLLE+UrQMD and AMPT SM
- NCQ scaling holds for hybrid models well

Sensitivity of the anisotropic flow to the EOS



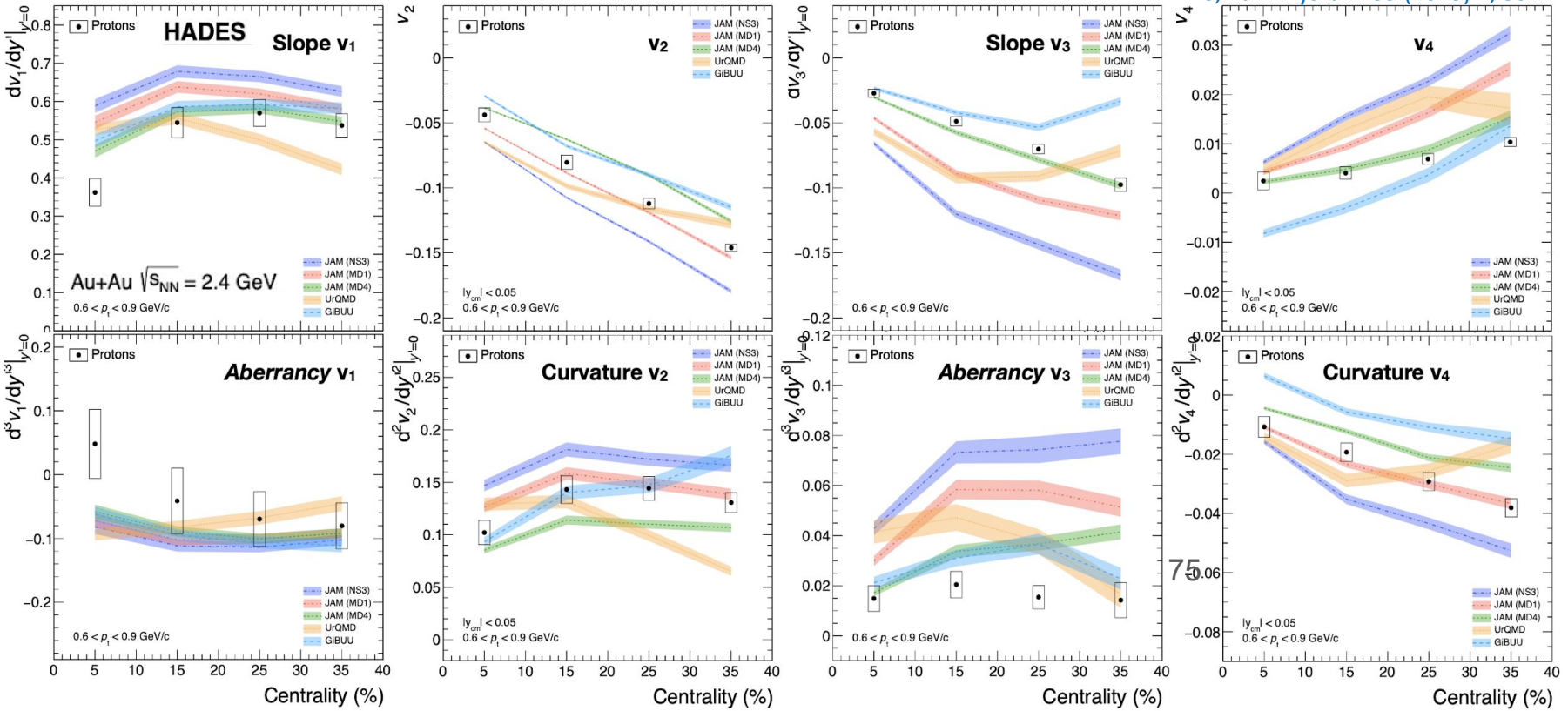
D. Oliinychenko et. al., Phys.Rev.C 108 (2023) 3, 034908

- SMASH model with flexible EOS was used to test the sensitivity of the v_n to changes of EOS in a specific density range n/n_0:
  - $2 < n_B < 3$: dv_1/dy' and v_2 of pions, protons and deuterons are very sensitive to the EOS
  - $3 < n_B < 4$: dv_1/dy' and v_2 of protons and deuterons are sensitive to the EOS
  - $3 < n_B < 4$: weak sensitivity to the EOS

The most precise constraints can be achieved from the flow of identified hadrons (pions, protons and deuterons)

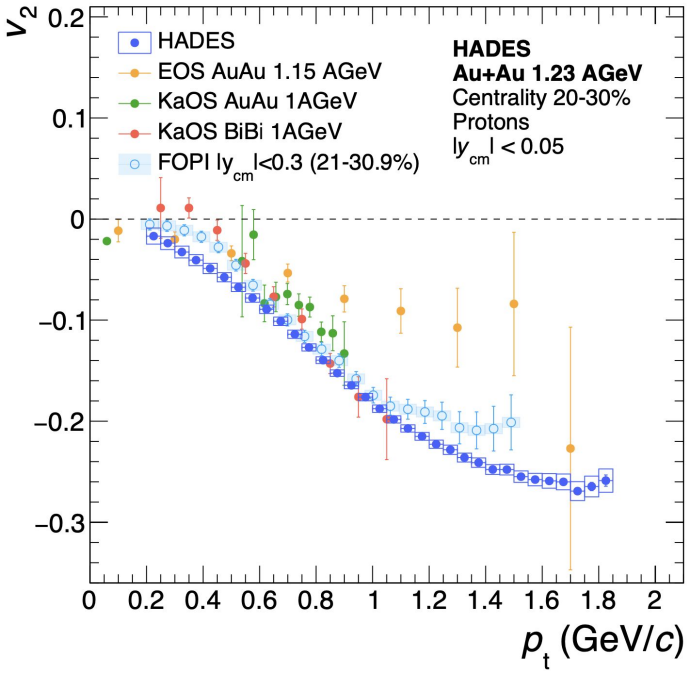
$v_n(y)$ in Au+Au $\sqrt{s_{NN}}$=2.4 GeV: models vs. HADES data

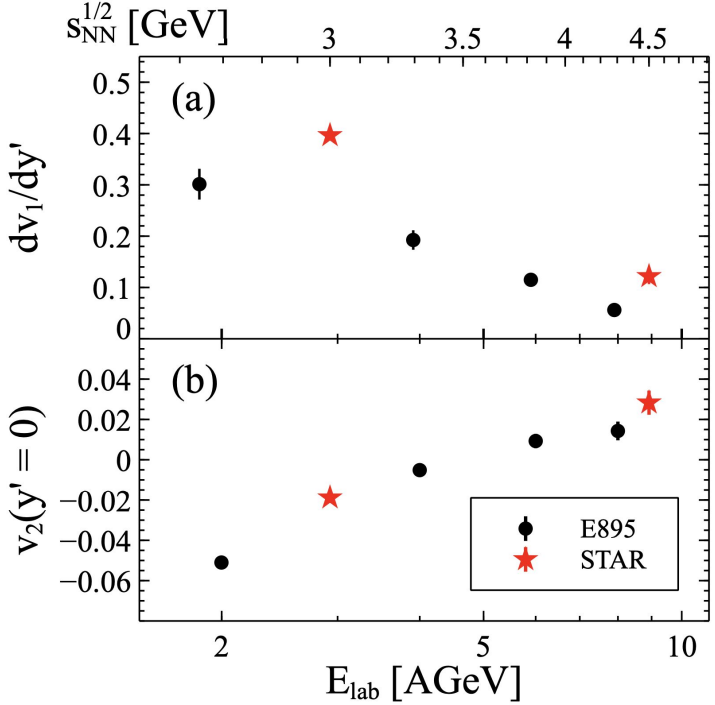
HADES, Eur. Phys. J. A 59 (2023) 4, 80



Overall trend reasonably well described, but no model works everywhere

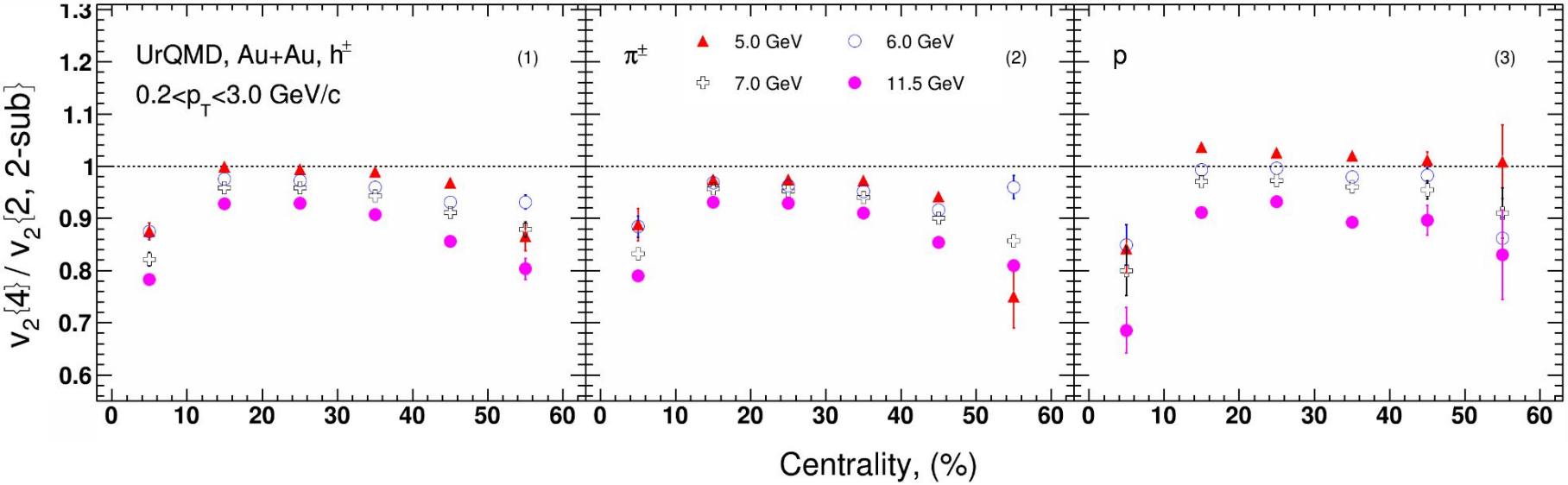
Why do we need new measurements at BM@N and MPD?





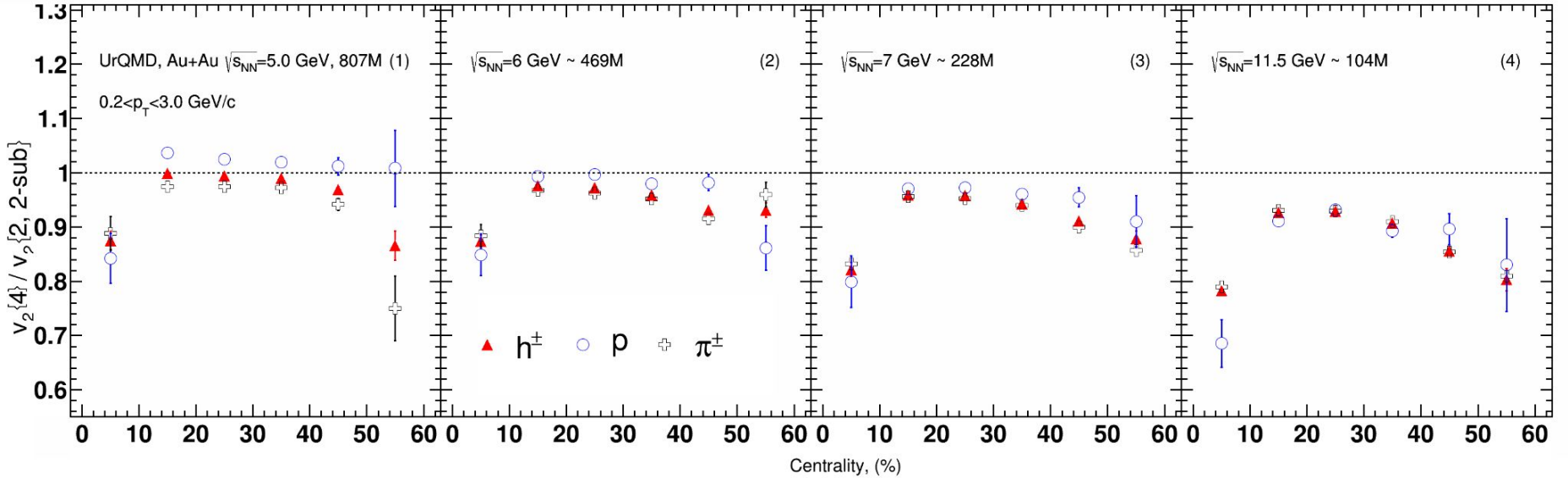
- The main source of existing systematic errors in v_n measurements is the difference between results from different experiments (for example, FOPI and HADES, E895 and STAR)
- New data from the future BM@N ($\sqrt{s_{NN}}$=2.3-3.3 GeV) and MPD ($\sqrt{s_{NN}}$=4-11 GeV) experiments will provide more detailed and robust v_n measurements

v_2 fluctuations at $\sqrt{s_{NN}}$ = 5 - 11.5 GeV



- v_2 fluctuations decrease with decreasing energy at NICA energy range at $\sqrt{s_{NN}}$ = 4-11.5 GeV
- The ratio $v_2\{4\}/v_2\{2\}$ has particle dependence

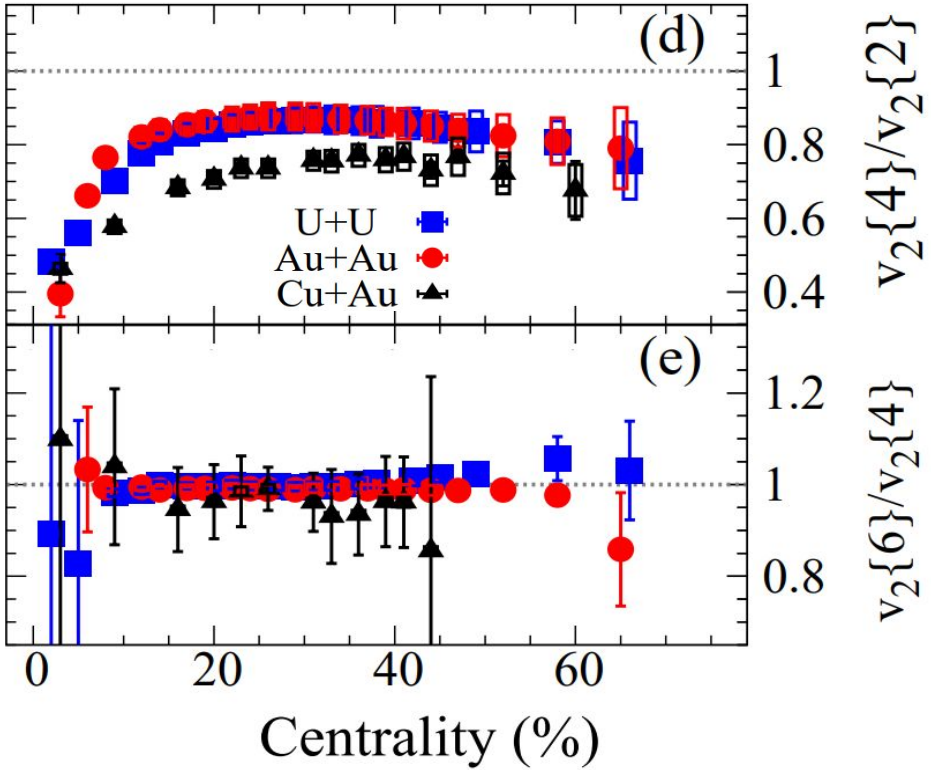
Relative v_2 fluctuations of identified hadrons



- v_2 fluctuations decrease with decreasing energy at NICA energy range at $\sqrt{s_{NN}}$ = 4-11.5 GeV
- The ratio $v_2\{4\}/v_2\{2\}$ has particle dependence

System size dependence of v_2 fluctuations

Phys. Rev. Lett. **129**, 252301



Different colliding system on a STAR:

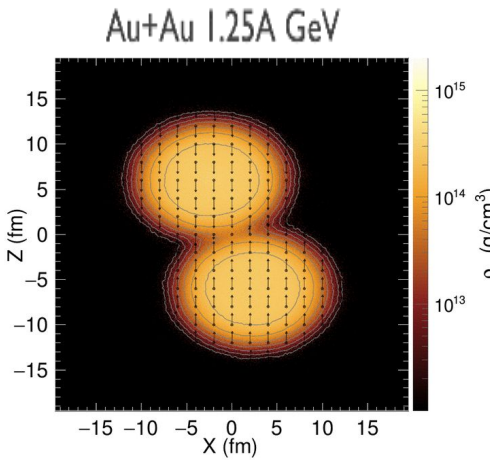
- U+U at 193 GeV
- Au+Au at 200 GeV
- Cu+Au at 200 GeV

Neutron star mergers in a lab?



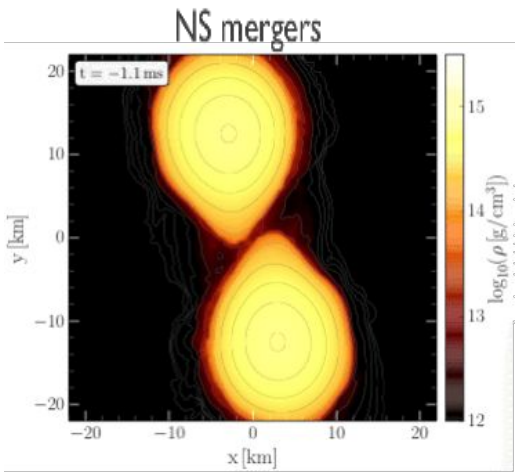
Copyright: Dana Berry, SkyWorks Digital, Inc

Heavy ion collisions



T<70 MeV, ρ≅3ρ$_0$

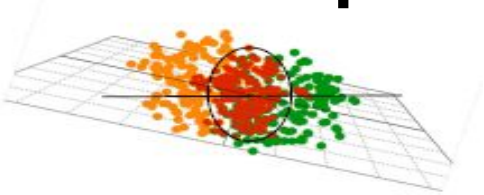
Neutron star mergers



T<70 MeV, ρ≅3ρ$_0$

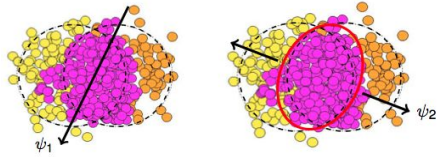
In terms of temperature and baryon density, heavy ion collisions at moderate and low beam energies can provide us with the strongly-interacting matter in a condition similar to the NS mergers

Anisotropic flow



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

v_1 - directed flow; v_2 - elliptic flow;

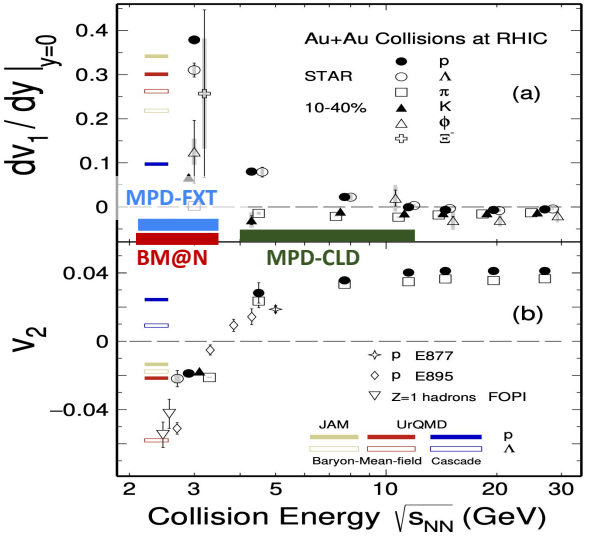


Phys.Rev.C 58 (1998) 1671-1678

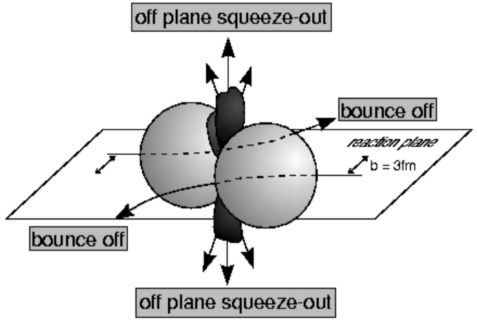
$$\frac{dN}{d\phi} \propto \left(1 + 2\sum_{n=1} v_n \cos\left[n\left(\phi - \Psi_n\right)\right]\right)$$

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

STAR, Phys.Lett.B 827 (2022) 137003



Initial eccentricity (and its attendant fluctuations) ϵ_n drive momentum anisotropy v_r with specific viscous modulation



At Nuclotron-NICA:

Strong energy dependence of dv_1/dy and v_2 at $\sqrt{s_{NN}}$=2-11 GeV

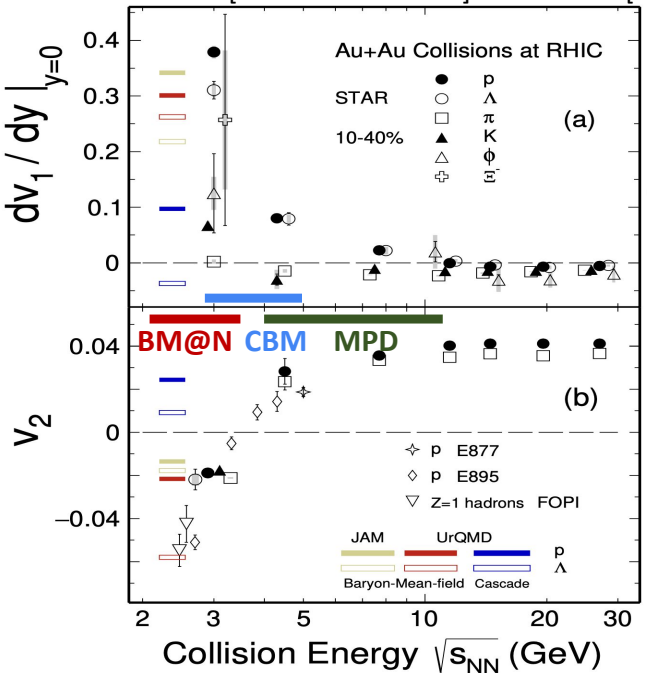
Anisotropic flow at Nuclotron-NICA energies is a delicate balance between:

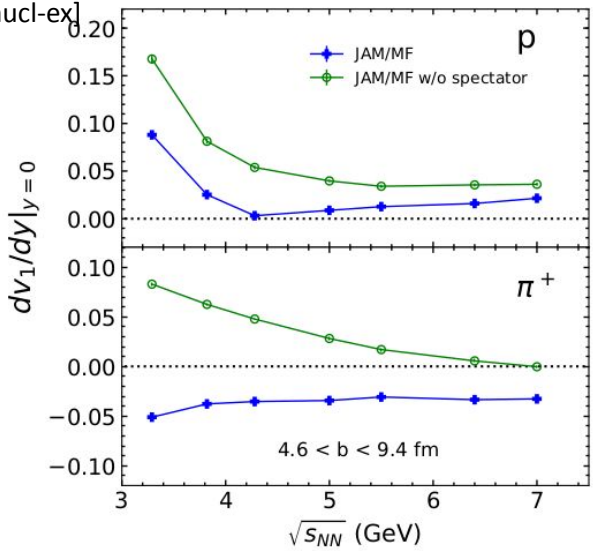
I. **The ability of pressure developed early in the reaction zone** ($t_{exp} = R/c_s$)

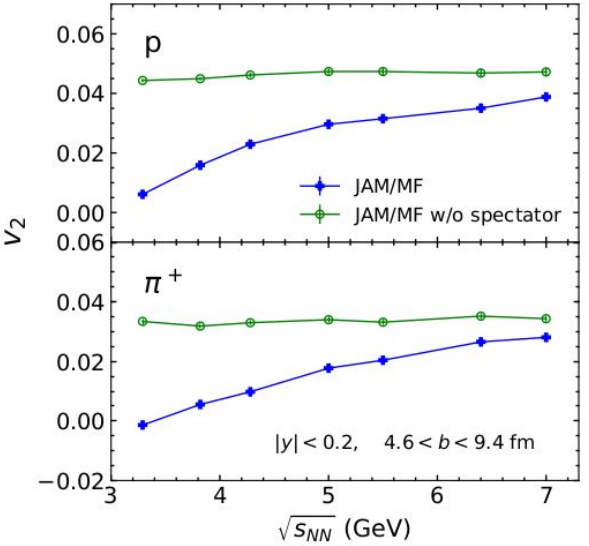
II. **The passage time for removal of the shadowing by spectators** ($t_{pass} = 2R/\gamma_{CM}\beta_{CM}$)

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

M. Abdallah et al. [STAR Collaboration] 2108.00908 [nucl-ex]







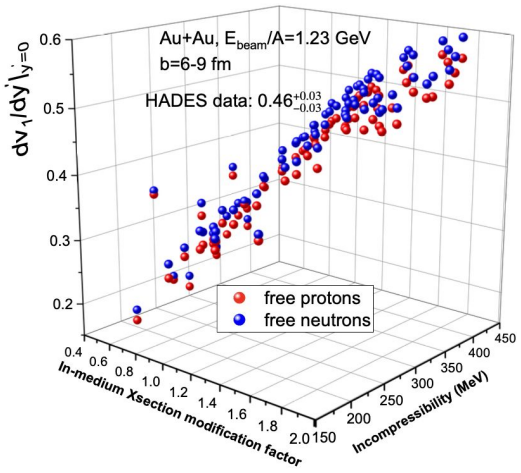
$$\frac{dN}{d\phi} \propto 1 + 2\sum_{n=1} v_n \cos[n(\phi - \Psi_{RP})], \qquad v_n = \langle \cos[n(\phi - \Psi_{RP})] \rangle$$

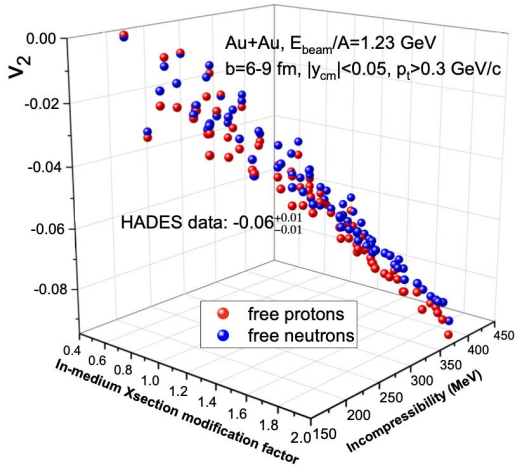
Anisotropic flow at FAIR/NICA energies is a delicate balance between:

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 ($t_{pass} = 2R/\gamma_{CM}\beta_{CM}$)

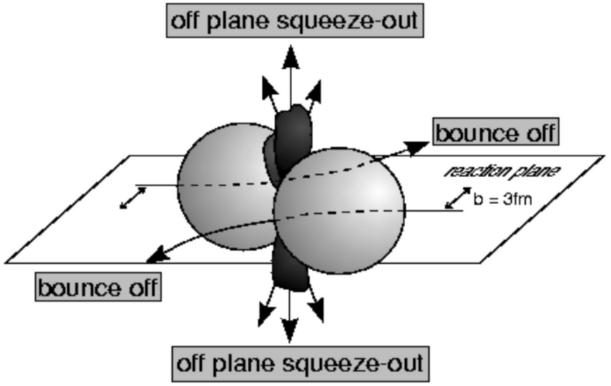
Sensitivity of the anisotropic flow to the EOS





Incompressibility K_0:
parameter which specifies the behavior of EOS in the given baryon densities $K_0 = K_0(\rho)$

Models with flexible EOS for different (K_0, ρ) are required



$$\frac{dN}{d\phi} \propto 1 + 2\sum_{n=1} v_n \cos[n(\phi - \Psi_{RP})], \qquad v_n = \langle \cos[n(\phi - \Psi_{RP})] \rangle$$

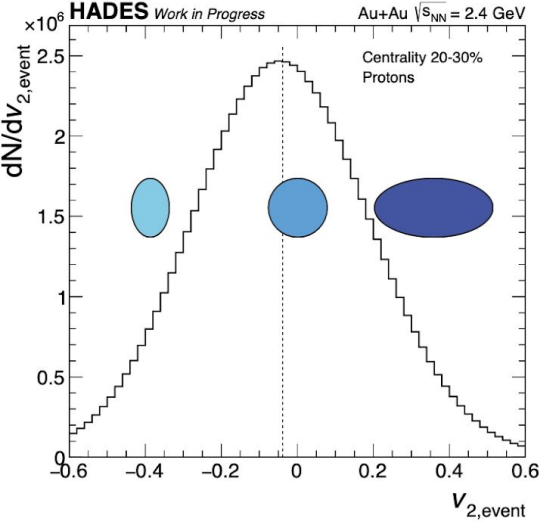
v_1 is called directed and v_2 is called elliptic flow

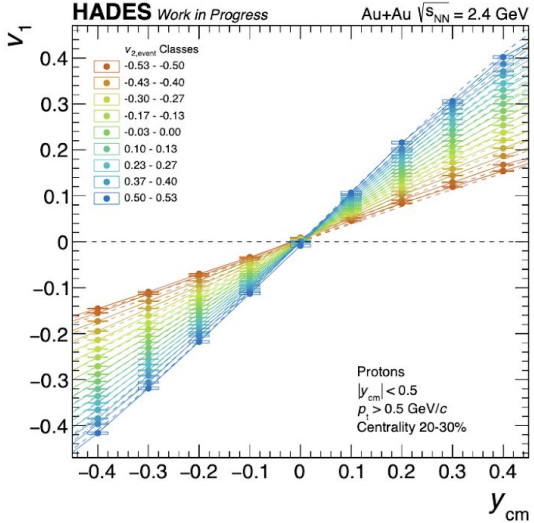
Collective flow is sensitive to:

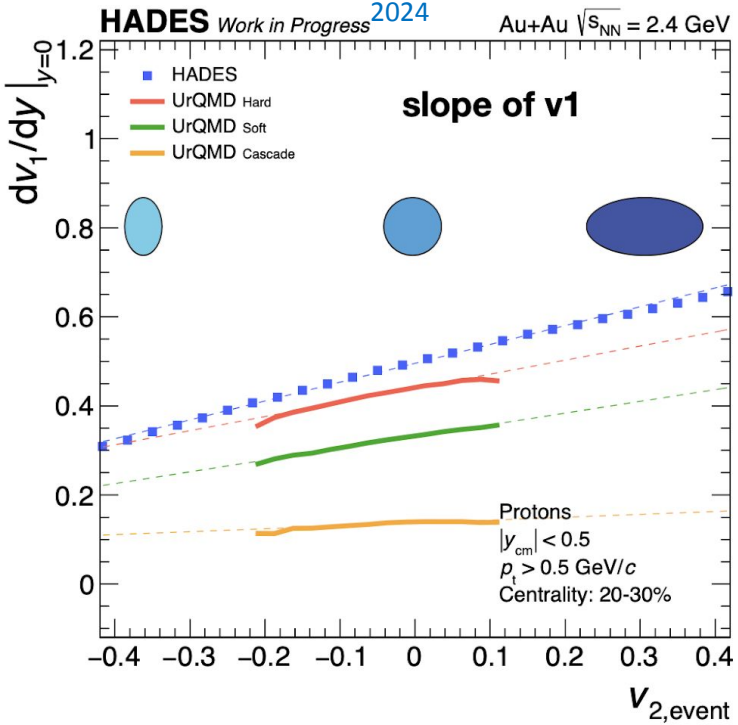
- **Compressibility of the created in the collision matter**
- **Time of the interaction between the matter within the overlap region and spectators**

Event-wise flow correlations

B. Kardan, EMMI Workshop 2024



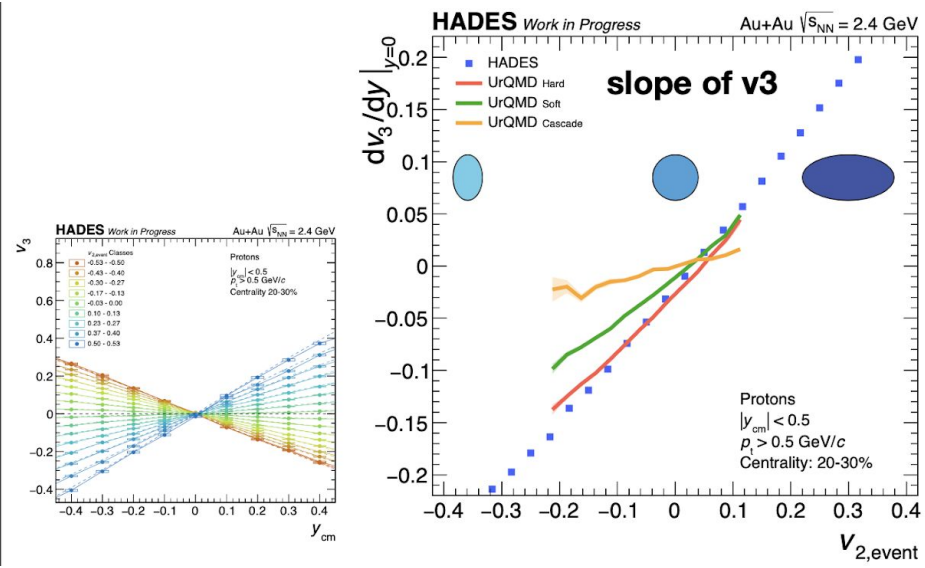




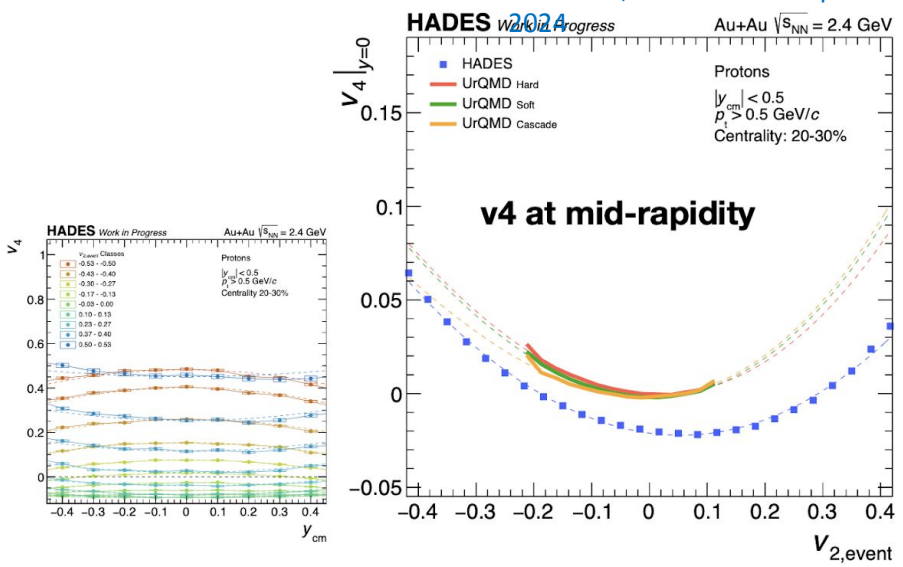
- Events can be characterized based on the event-wise magnitude of the elliptic flow $v_{2,event}$
- UrQMD can not discribe $dv_1/dy|_{y=0}$ of protons as a function of $v_{2,event}$
- Strong sensitivity to the EOS

Event-wise flow correlations

B. Kardan, EMMI Workshop 2024



$dv_3/dy|_{y=0}$ of protons as a function of $v_{2,event}$ shows strong sensitivity to EoS

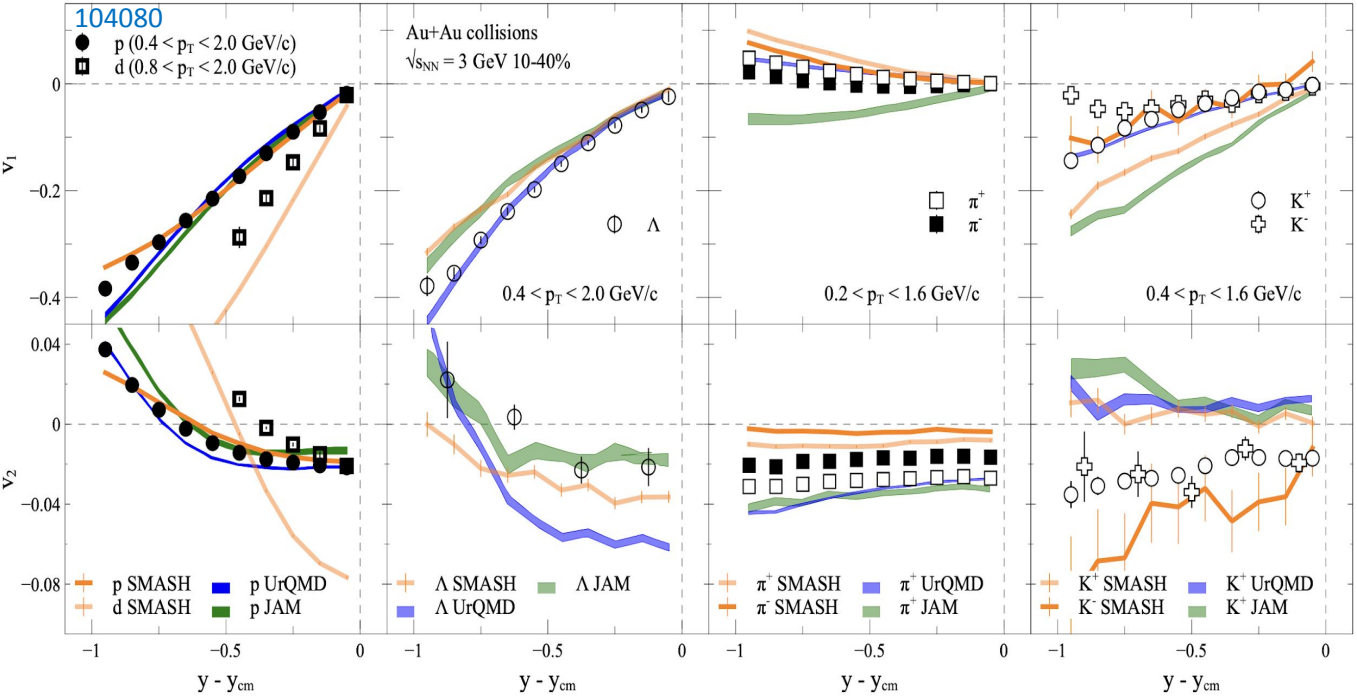


Models overestimate v_4 of protons as a function of $v_{2,event}$ compared to the HADES data

Mean-field models do not reproduce experimental data on the event-wise flow correlations of protons

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

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



Model description of v_n:

- Good overall agreement for v_n of protons
- v_n of light nuclei is not described
- v_n of Λ is not well described
  - **nucleon-hyperon** and **hyperon-hyperon** interactions
- Light mesons (π,K) are not described
  - No mean-field for mesons

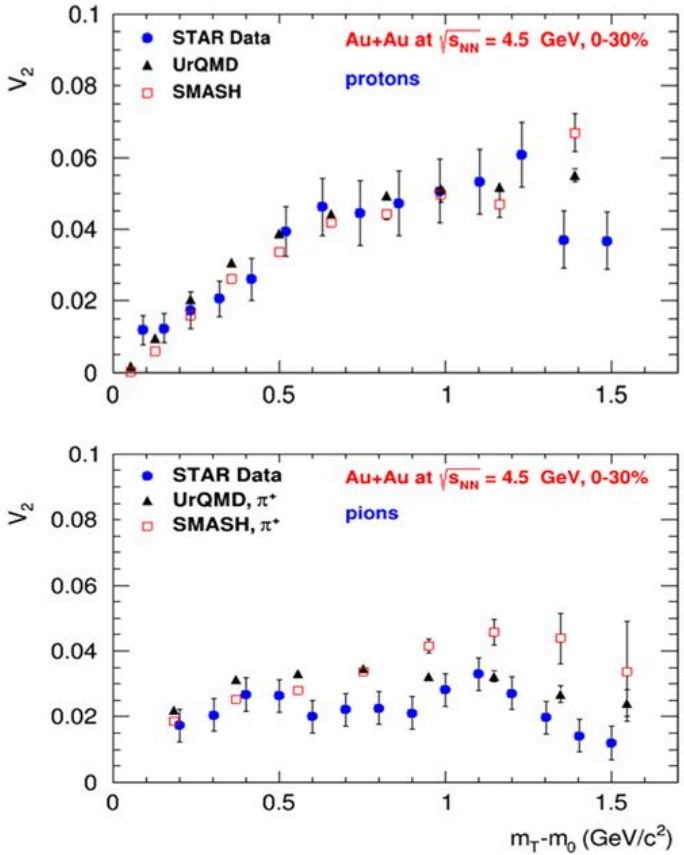
Models have a huge room for improvement in terms of describing v_n

Data set / Motivation

- Colliding system: Au-Au
- UrQMD data:
  - 5 GeV ~ 800M
  - 6 GeV ~ 500M
  - 7 GeV ~ 230M
  - 11.5 GeV ~ 110M
- Centrality determination: b-based
- Track selection:
  - $0.2 < p_T < 3.0$ GeV/c
  - $| \eta | < 1.5$
  - PID based on PDG-code

- UrQMD at ~5 GeV reproduces STAR data

Particles 2022, 5(4), 561-579



The purpose of comparisons between models and existing data

Objectives:

- Conduct a consistent comparative analysis using the same measurement methods as in the experiments
- Hybrid constructor with the ability to vary models (and their parameters) for describing different collision stages
- Development of Bayesian analysis tools

