Anisotropic collective flow and development of the corresponding measurement techniques for the MPD experiment

Alexander Demanov[1], Dim Idrisov[1], Vinh Ba Luong[1,2], Nikolay Geraksiev[2,3], Petr Parfenov[1] ,Viktor Kireyeu[2] , Evgeny Volodihin[1] , Anton Truttse[1], Mikhail Mamaev[1] , Dmitri Blau[4] , Oleg Golosov[1] , Evgeni Kashirin[1] , Jovan Milošević[6] ,Laslo Nađđerđ[6], Vladimir Reković[6], Dragan Toprek[6], Ilya Segal[1] , Dragan Manić[6], Valery Troshin[1] , Arkadiy Taranenko[1]

With big help from Andrey Moshkin (VBLHEP JINR) and Dmitry Podgainy (LIT, JINR)

[1]National Research Nuclear University MEPhI
[2]VBLHEP JINR
[3]FPT, Plovdiv University “Paisii Hilendarski”
[4]Kurchatov Institute, Moscow,
[6]Vinča Institute of Nuclear Sciences, University of Belgrade, Serbia

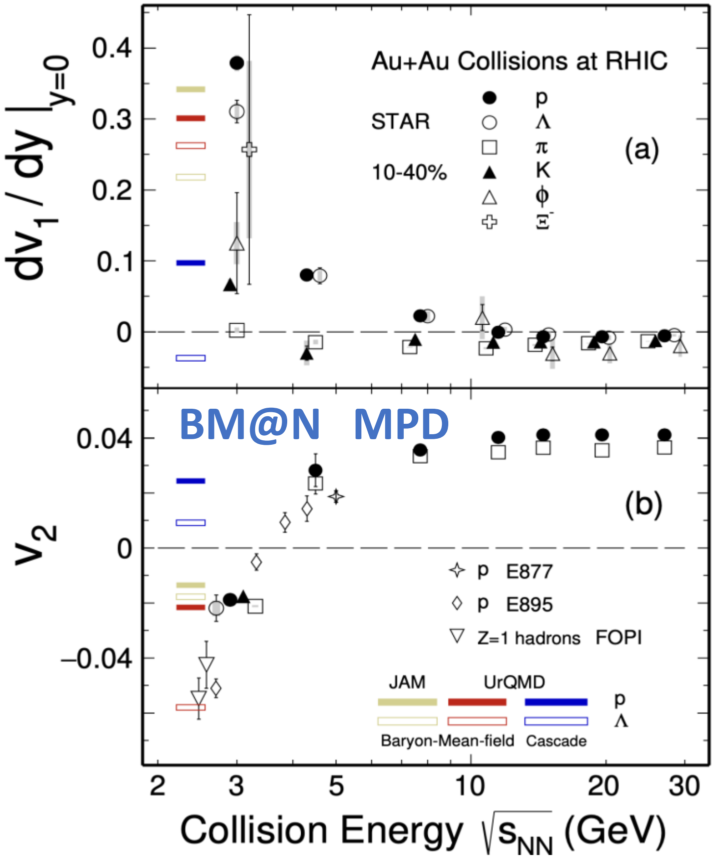
For the MPD Collaboration

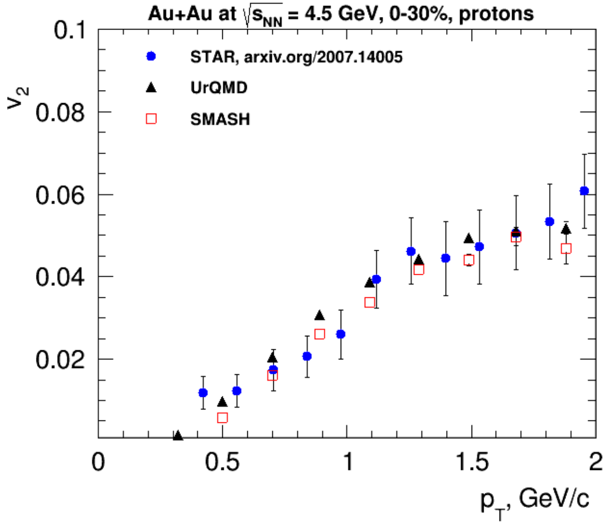
10th MPD Collaboration Meeting, JINR , Dubna, 8-10 November 2022

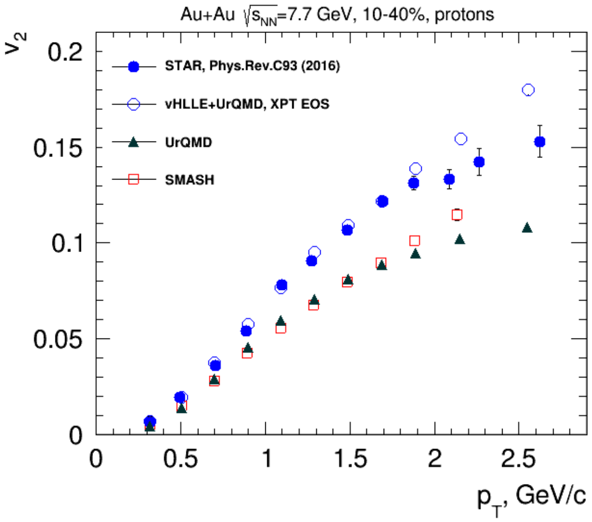
This work is supported by: the NRNU program Priority 2030 and Special Purpose Funding Programme within the NICA Megascience Project in 2022

Anisotropic flow at NICA energies

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



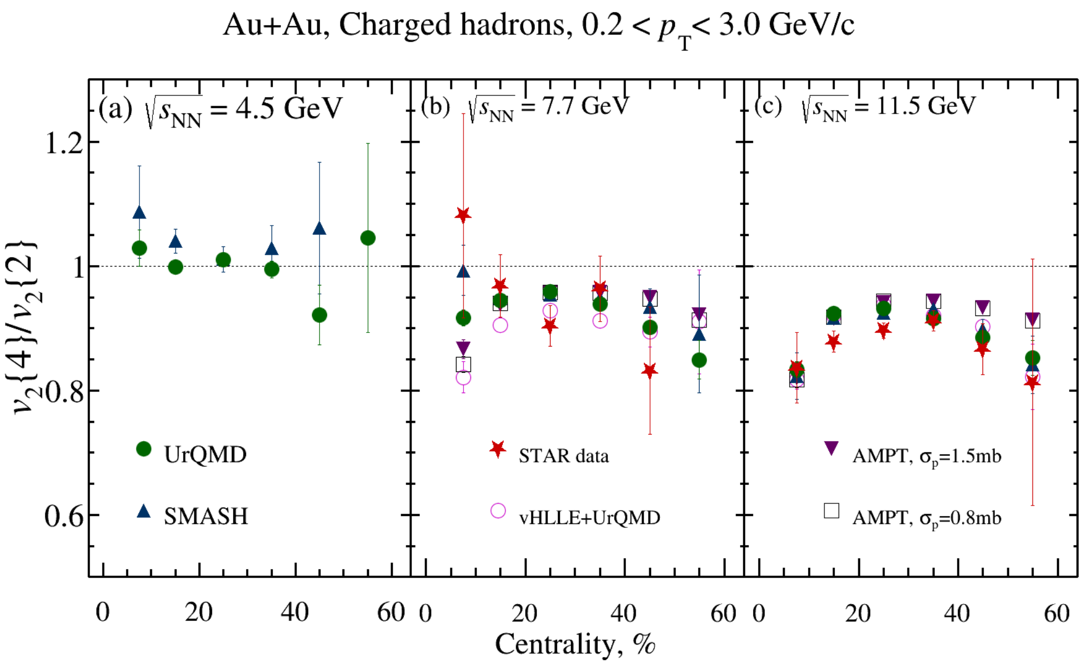




- **Strong energy dependence of v_1 and v_2 at $\sqrt{s_{NN}}$ = 3-11 GeV**
  - $v_2 \approx 0$ at $\sqrt{s_{NN}}$ = 3.3 GeV and negative below
- **Lack of differential measurements of v_2 at NICA energies (p_T, centrality, PID,…)**
- **v_2 is sensitive to the properties of strongly interacting matter:**
  - at $\sqrt{s_{NN}}$ = 4.5 GeV pure string/hadronic cascade models (UrQMD, SMASH,…) give similar v_2 signal compared to STAR data
  - at $\sqrt{s_{NN}} \geq$ 7.7 GeV pure string/hadronic cascade models underestimate v_2 – need hybrid models with QGP phase (vHLLE+UrQMD, AMPT with string melting,…)

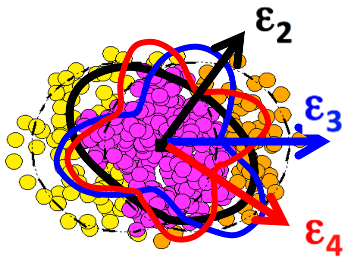
- Make predictions for the anisotropic flow measurements $v_n(p_T, y)$ at BM@N ($\sqrt{s_{NN}}$=2.3-3.3 GeV) and MPD ($\sqrt{s_{NN}}$=4-11 GeV) energies

Relative flow fluctuations of charged hadrons

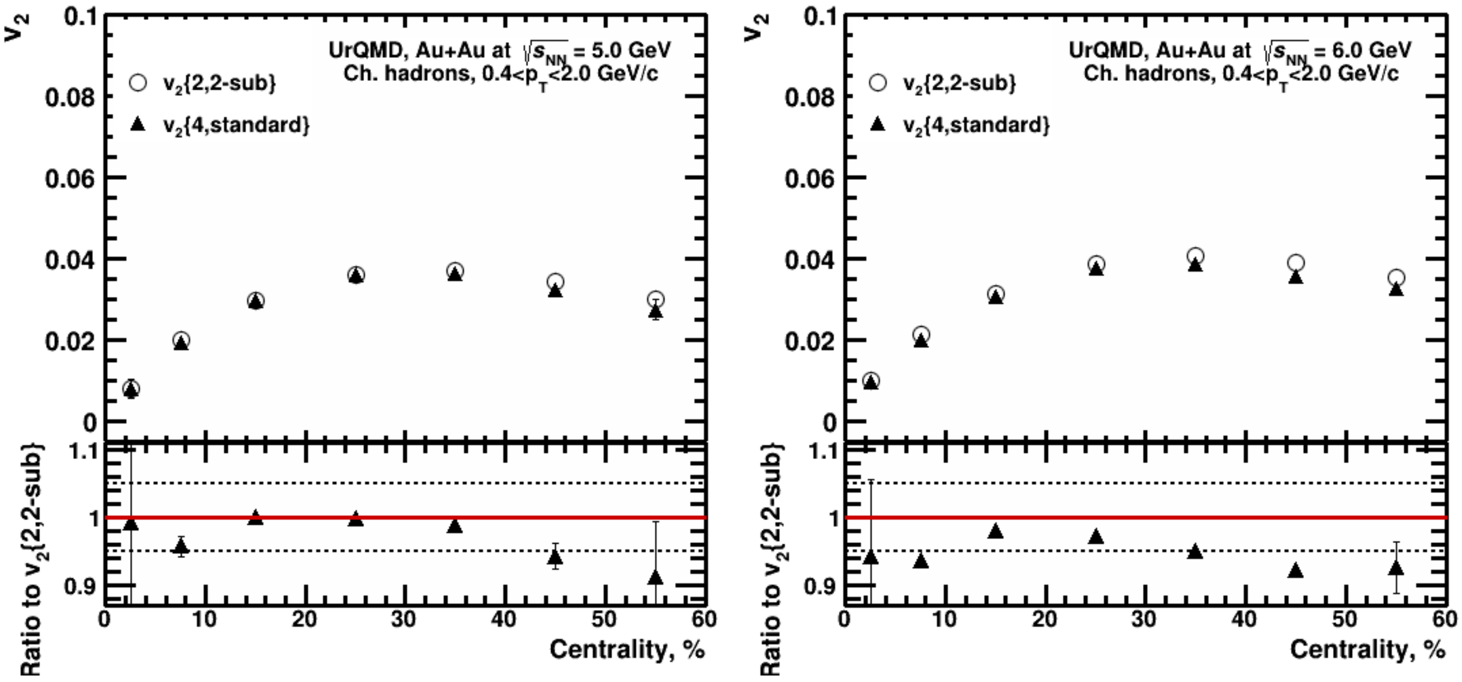


STAR data: Phys.Rev.C **86**, 054908 (2012)

- Relative v_2 fluctuations ($v_2\{4\}/v_2\{2\}$) observed by STAR experiment can be reproduced both in the string/cascade models (UrQMD, SMASH) and model with QGP phase (AMPT SM, vHLLE+UrQMD)
- Dominant source of v_2 fluctuations: **participant eccentricity fluctuations** in the initial geometry
- Are there non-zero v_2 fluctuations at $\sqrt{s_{NN}}$= 4.5 GeV?



Relative v_2 fluctuations of charged hadrons



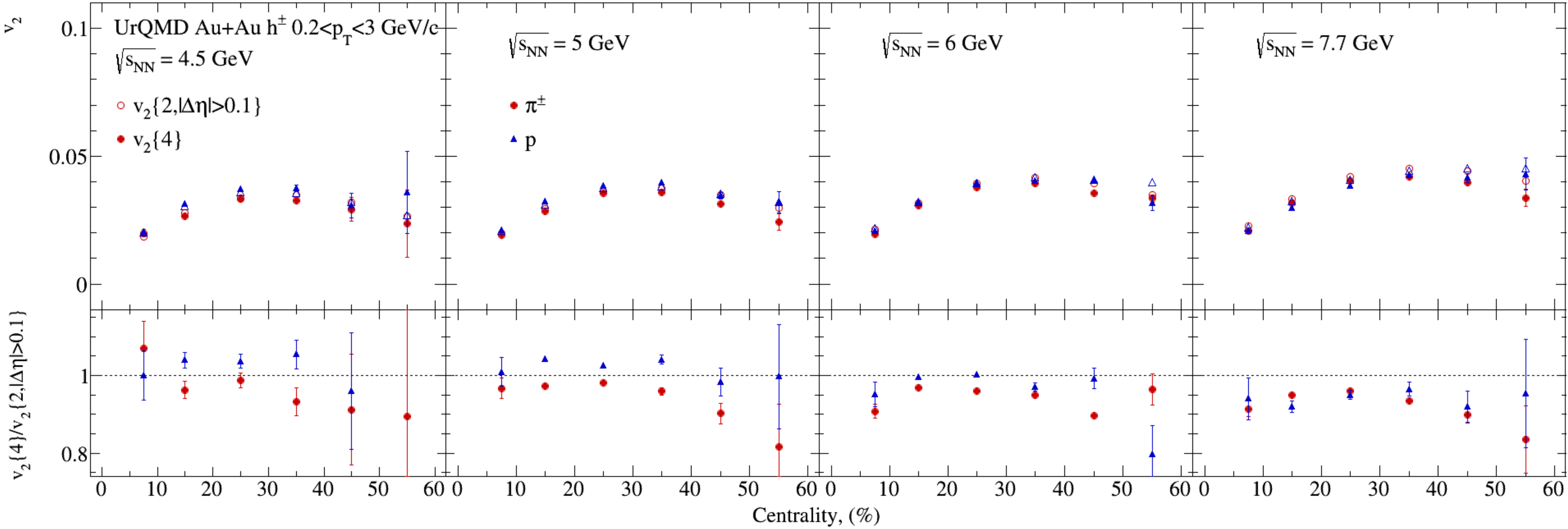
UrQMD v3.4, cascade mode

- **$\sqrt{s_{NN}}$=5 GeV: 230M**
- **$\sqrt{s_{NN}}$=6 GeV: 270M**

$|\eta| < 1.5$, η-gap: $|\Delta\eta| > 0.1$

- $v_2\{4\} \approx v_2\{2\}$ in mid-central collisions at $\sqrt{s_{NN}}$=5 GeV
- $v_2\{4\}/v_2\{2\}$ shows 2-4% difference in mid-central collisions at $\sqrt{s_{NN}}$=6 GeV

Relative v_2 fluctuations of pions and protons



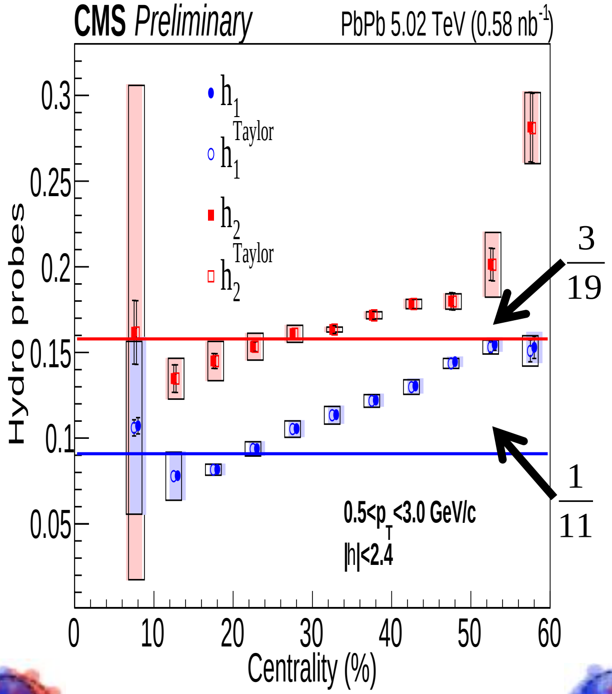
- $v_2\{4\}\ /v_2\{2\}$ differs for pions and protons at $\sqrt{s_{NN}} < 6$ GeV
- $v_2\{4\}\ /v_2\{2\} < 1$ at $\sqrt{s_{NN}} > 5$ GeV for pions and at $\sqrt{s_{NN}} > 6$ GeV for protons

High-Order Cumulants: Hydro probes & central moments

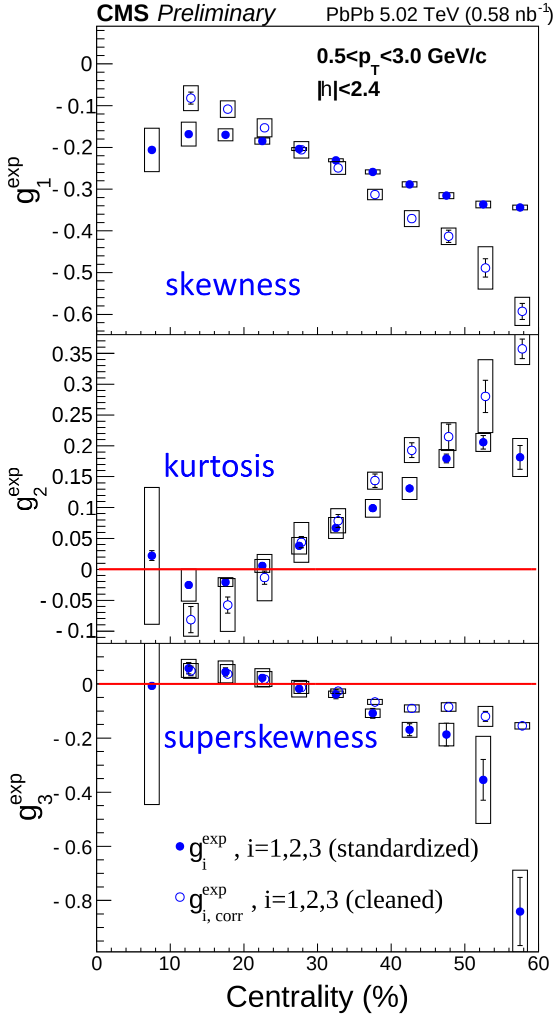
$$h_1 = \frac{v_2\{6\} - v_2\{8\}}{v_2\{4\} - v_2\{6\}} \approx h_1^{Taylor} = \frac{1}{11} - \frac{1}{11}\frac{v_2^2\{4\} - 12v_2^2\{6\} + 11v_2^2\{8\}}{v_2\{4\}^2 - v_2\{6\}^2}$$

$$h_2 = \frac{v_2\{8\} - v_2\{10\}}{v_2\{6\} - v_2\{8\}} \approx h_2^{Taylor} = \frac{3}{19} - \frac{1}{19}\frac{3v_2^2\{6\} - 22v_2^2\{8\} + 19v_2^2\{10\}}{v_2\{6\}^2 - v_2\{8\}^2}$$

$$\gamma_1^{\mathrm{exp}} = -2^{3/2}\frac{v_2\{4\}^3 - v_2\{6\}^3}{\left[v_2\{2\}^2 - v_2\{4\}^2\right]^{3/2}} \approx -2^{3/2}\frac{-s_{30} - O_N}{\left[2\sigma_x^2 + O_D\right]^{3/2}} \approx \frac{s_{30}}{\sigma_x^3} \equiv \gamma_1$$



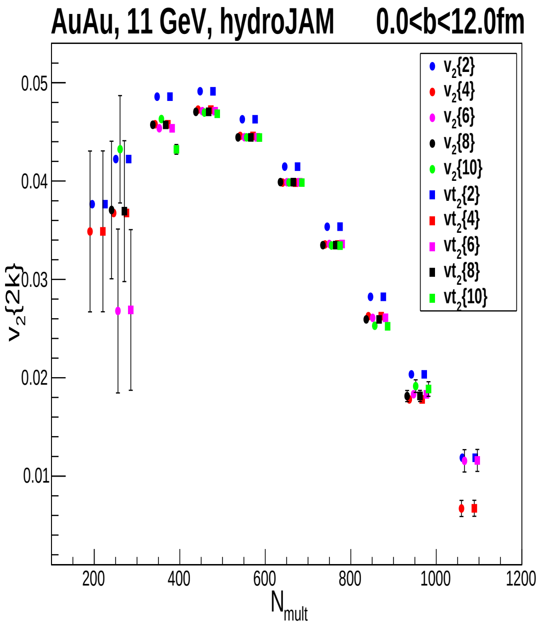
Higher-order moments necessary to describe data

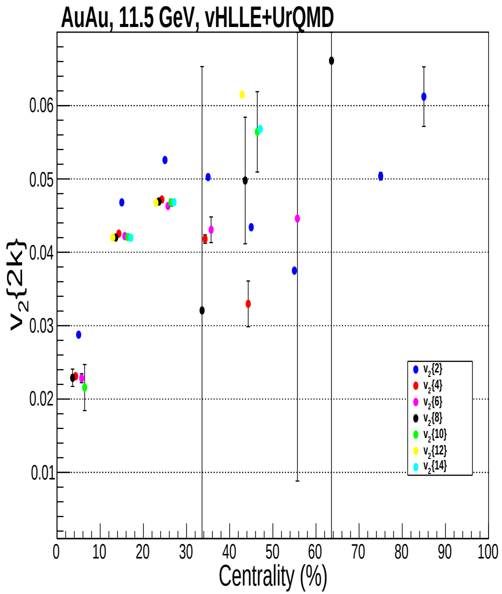


NICA energy case

- ✧ AuAu collisions at $\sqrt{s_{NN}}$ = 11.0 GeV
- In 10 multiplicity/centrality classes

- 0.0 < b < 12.0 fm
- JAM stat.: 1.068 B events
- vHLLE stat. 34 M events





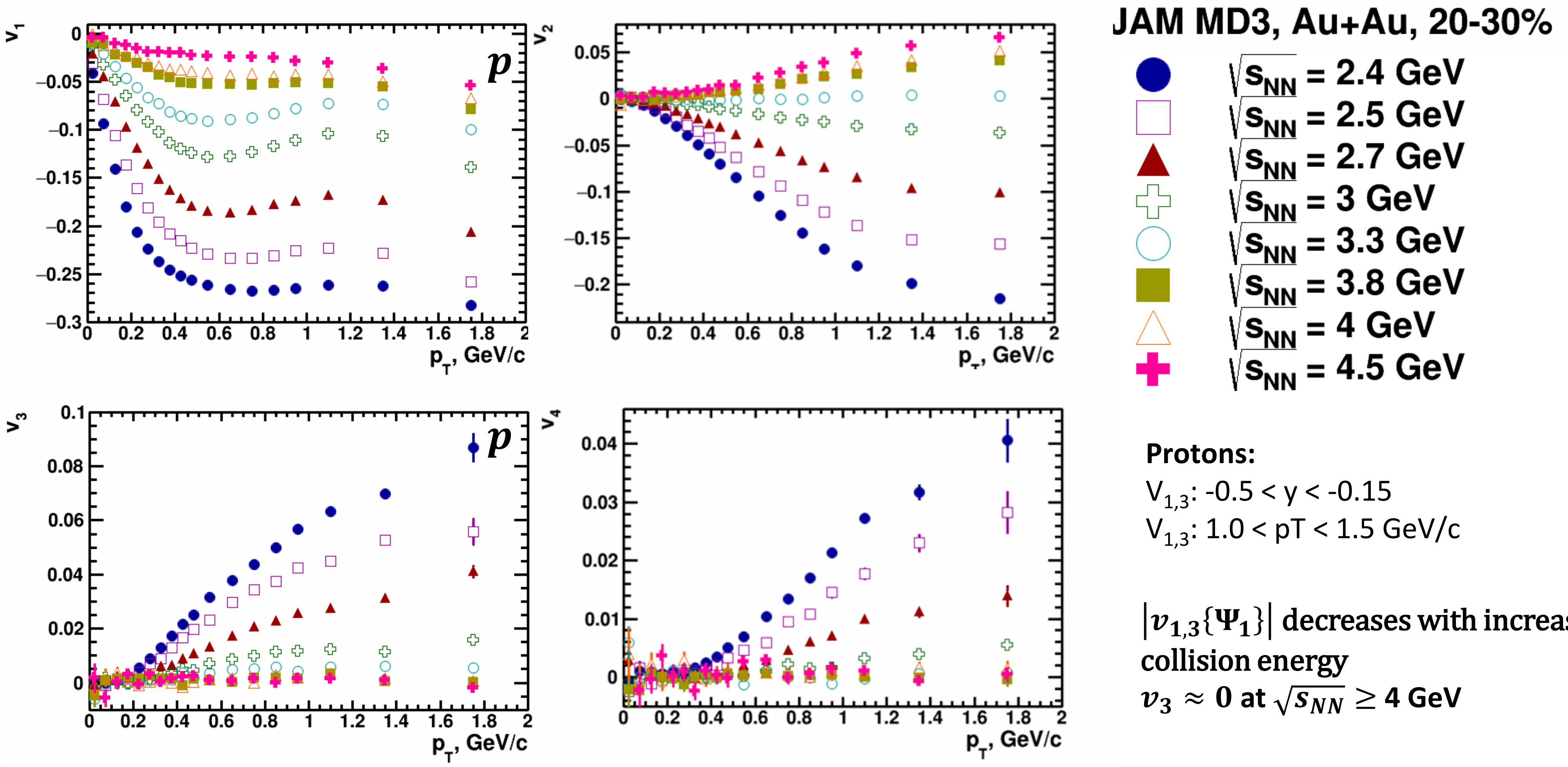
Necessary condition $v_2\{4\} > v_2\{6\} > v_2\{8\} > v_2\{10\}$ **to perform hydro probes and to measure central moments**

It seems JAM does not have splitting

vHLLE should have splitting, but current statistics is too small

Statistics of the real MPD should be about 1B (10^9) events per year that enables performing hydro probes and central moments measurements

$v_{1,2,3,4}(p_T)$ Au+Au $\sqrt{s_{NN}}$=2.4-4.5 GeV: BM@N+MPD



Protons:

$V_{1,3}$: -0.5 < y < -0.15

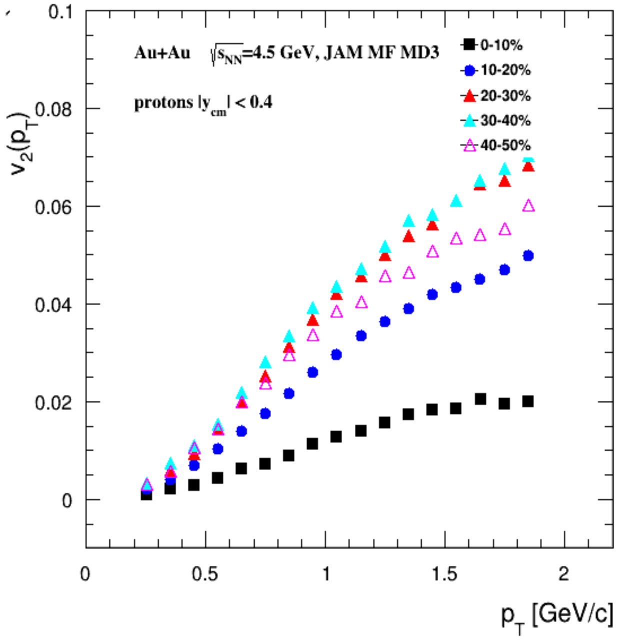
$V_{1,3}$: 1.0 < pT < 1.5 GeV/c

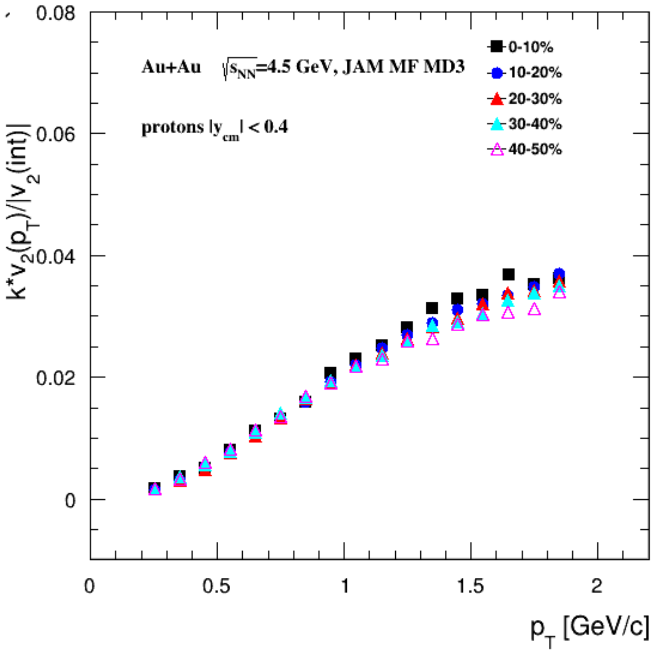
$|v_{1,3}\{\Psi_1\}|$ decreases with increasing collision energy

$v_3 \approx 0$ **at** $\sqrt{s_{NN}} \geq$ **4 GeV**

Scaling with integral flow of charged hadrons. Will it work at $\sqrt{s_{NN}}$ =4.5 GeV? (JAM mean field MD3)

See Peter Parfenov talk



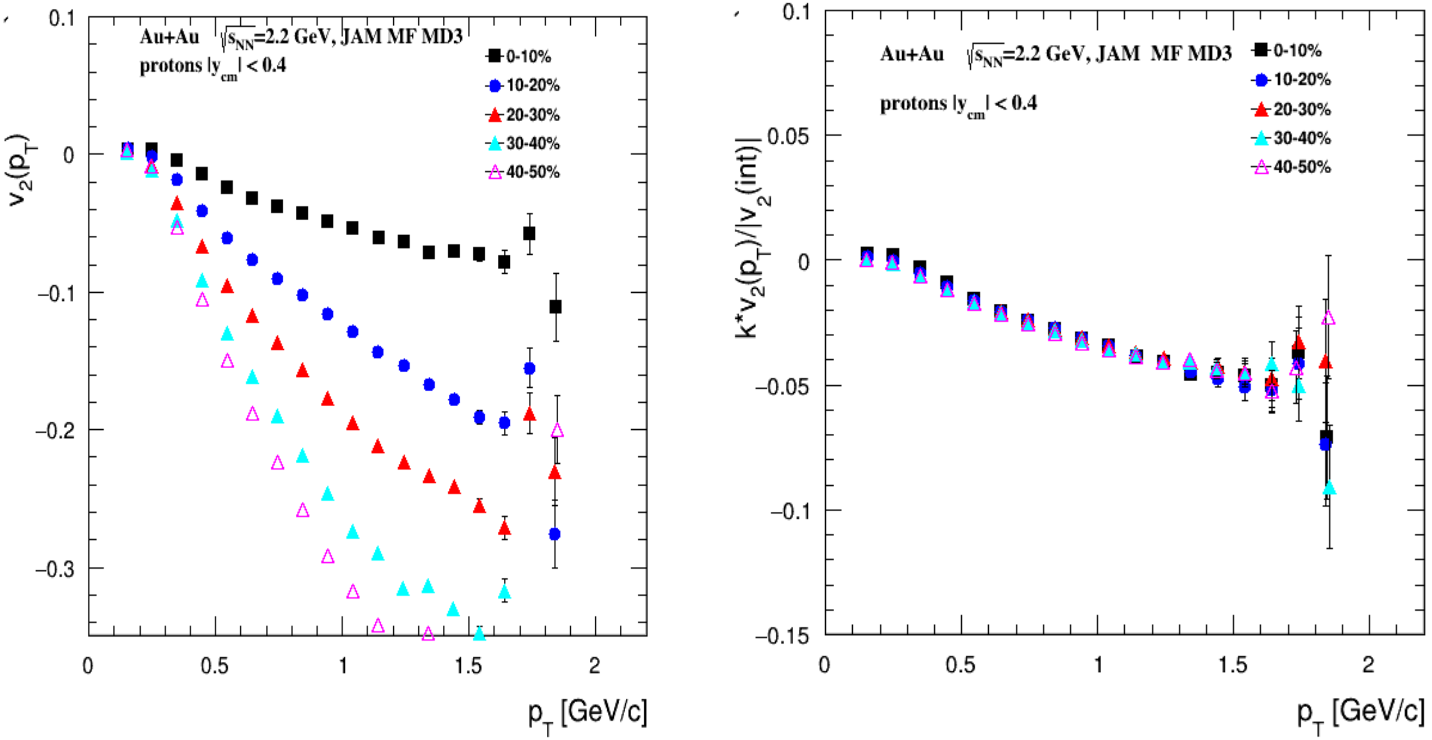


Scaling starts to work again – after the transition from out-of-plane to in-plane

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

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

See Peter Parfenov talk

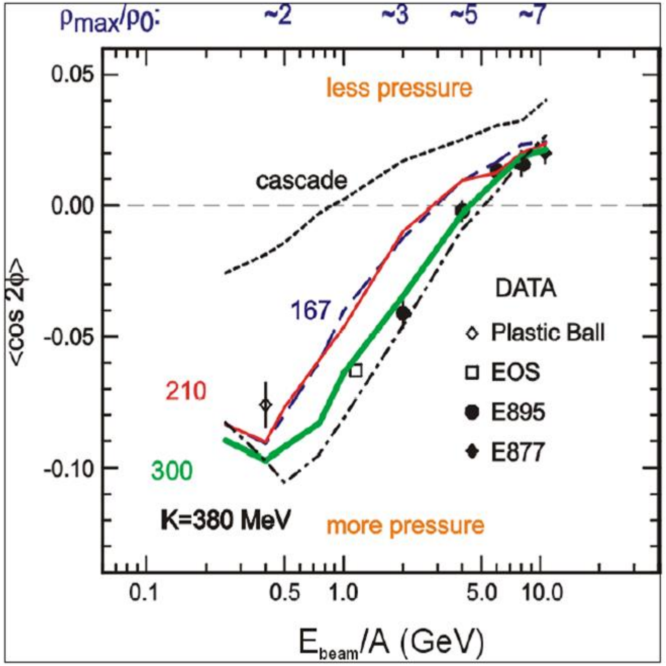


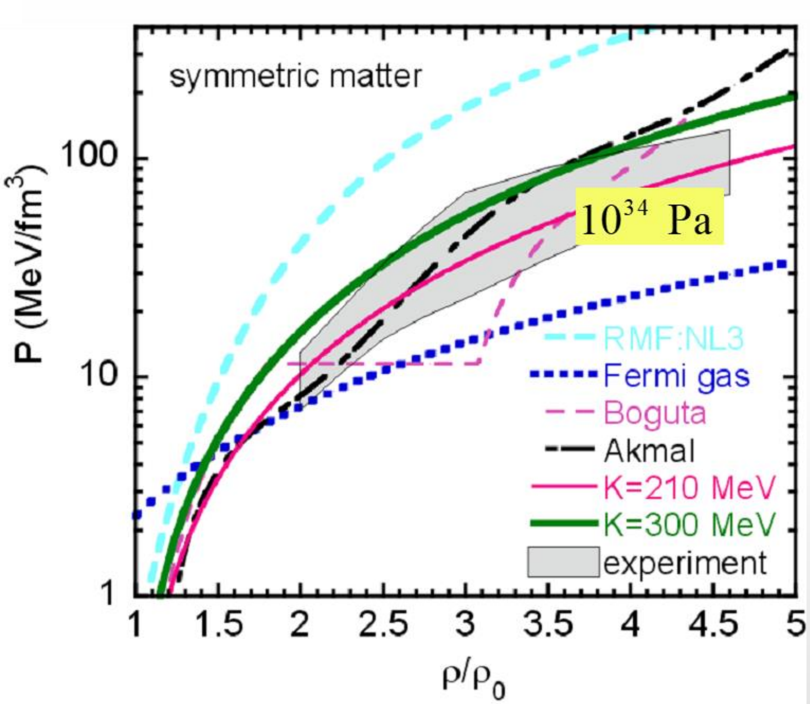
In all plots k=0.025 and v2(int) for 0.4<pT<2.0 GeV/c

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

Flow at AGS: 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**

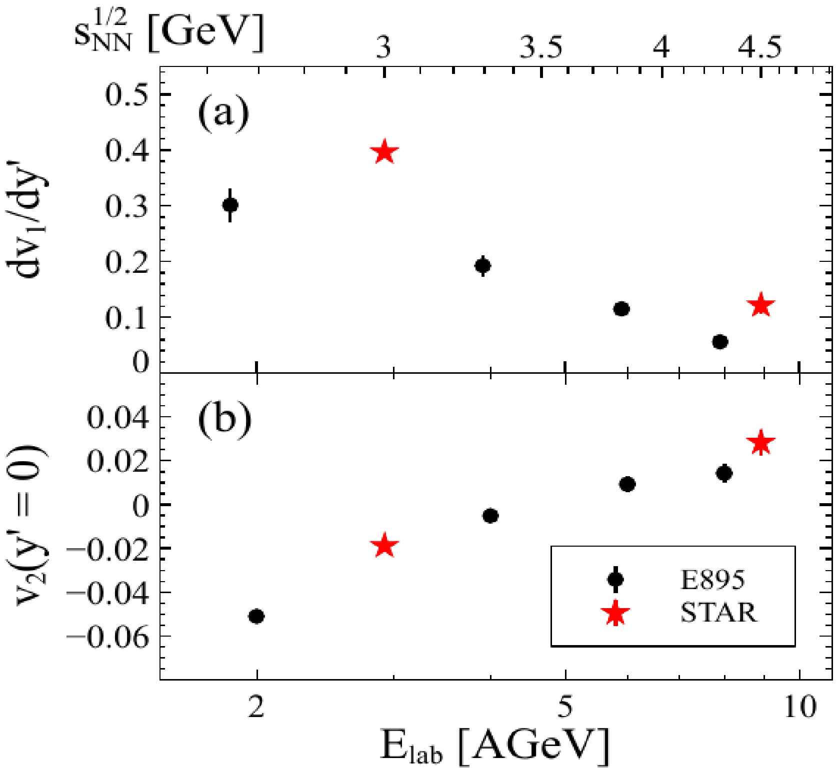
c_s=c√dp/dε - speed of sound

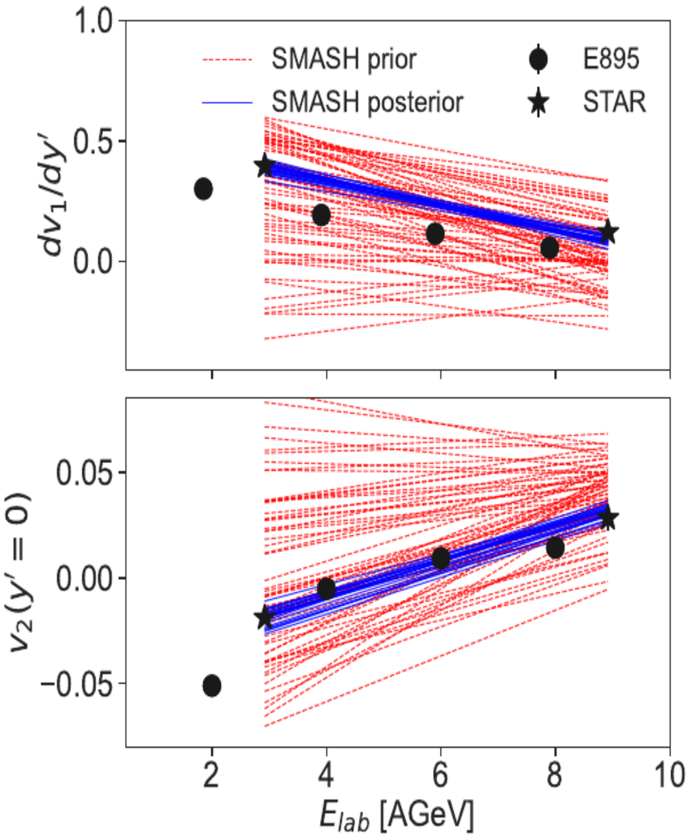
$$c_s = \sqrt{K/9m_N} \approx 0.15c, 0.21c$$

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

Sensitivity of Au+Au collisions to the symmetric nuclear matter equation of state at 2–5 nuclear saturation densities

Dmytro Oliinychenko,[1,*] Agnieszka Sorensen,[1,†] Volker Koch,[2] and Larry McLerran[1]
[1] Institute for Nuclear Theory, University of Washington, Box 351550, Seattle, Washington 98195, USA
[2] Lawrence Berkeley National Laboratory, 1 Cyclotron Road, Berkeley, California 94720, USA



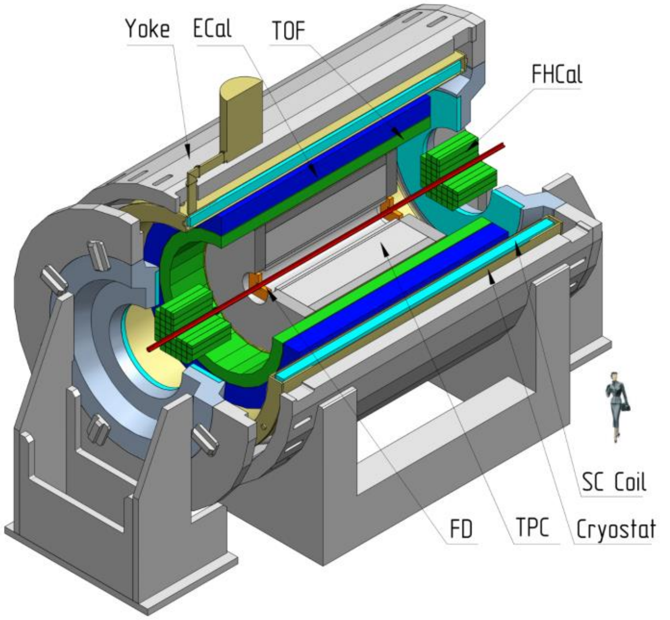


MPD Experiment at NICA

UrQMD → GEANT4 → Reconstruction → Flow analysis

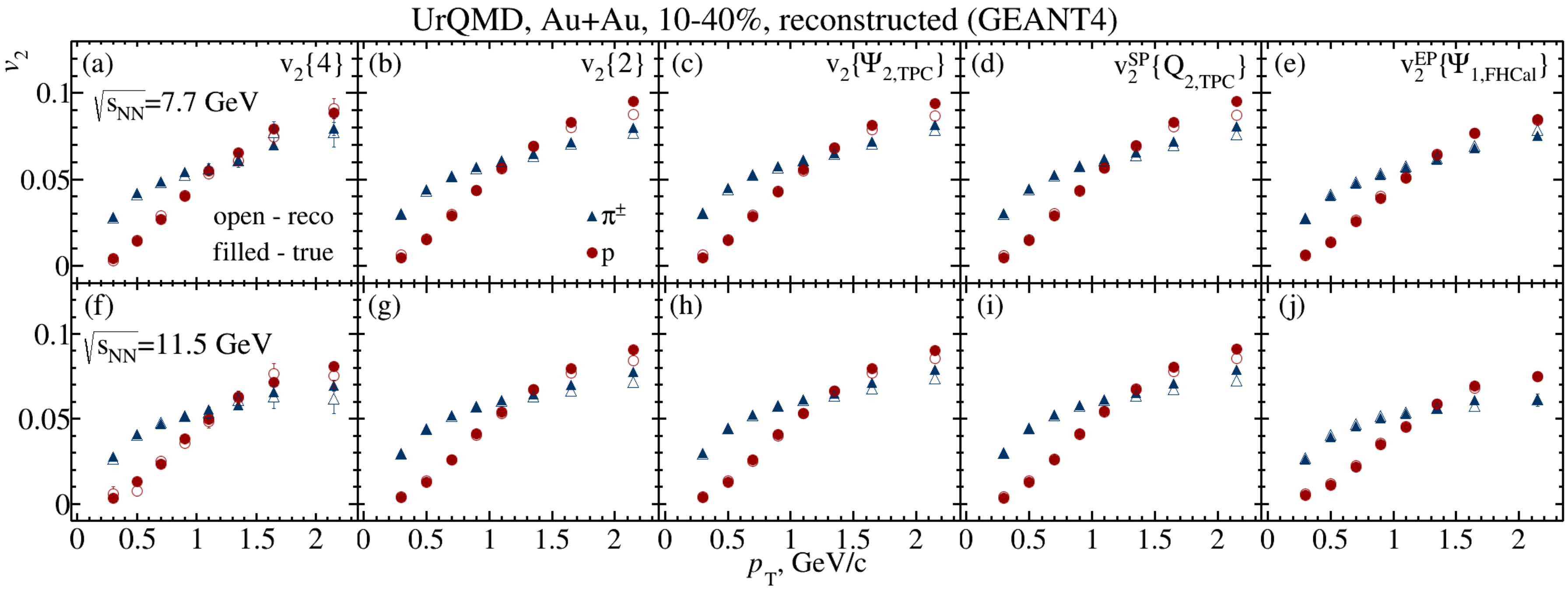
- Au+Au: 20M at $\sqrt{s_{NN}}$ = 7.7 GeV, 10M at $\sqrt{s_{NN}}$ = 11.5 GeV,
  Bi+Bi: 5M at $\sqrt{s_{NN}}$ = 9.2, 7.7, 4.5 GeV
  Ag+Ag 5M at $\sqrt{s_{NN}}$ = 9.2, 4.5 GeV
- Centrality determination: Bayesian inversion method and MC-Glauber
- Event plane determination: TPC, FHCal
- Track selection:
  - Primary tracks
  - $N_{TPC\ hits} \geq 16$
  - $0.2 < p_T < 3.0$ GeV/c
  - $|\eta| < 1.5$
  - PID – ToF + dE/dx

$-5<\eta<-2$	$-1.5<\eta<1.5$	$2<\eta<5$
FHCal	TPC $0.2<p_T<3$ GeV/c	FHCal



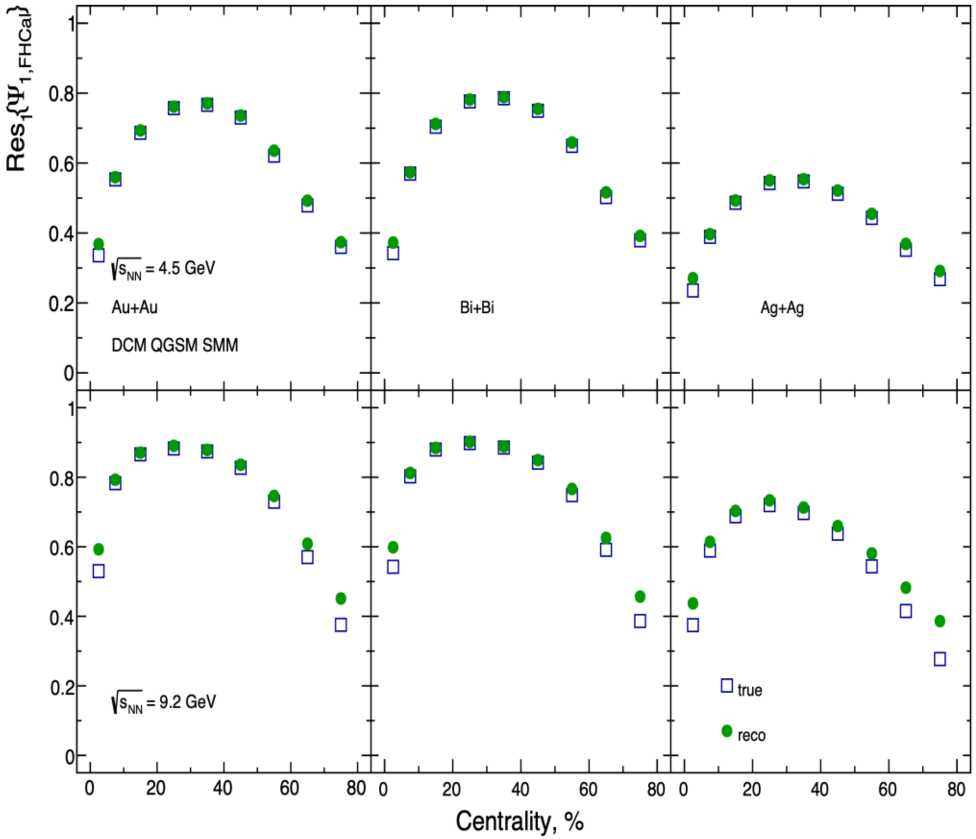
Multi-Purpose Detector (MPD) Stage 1

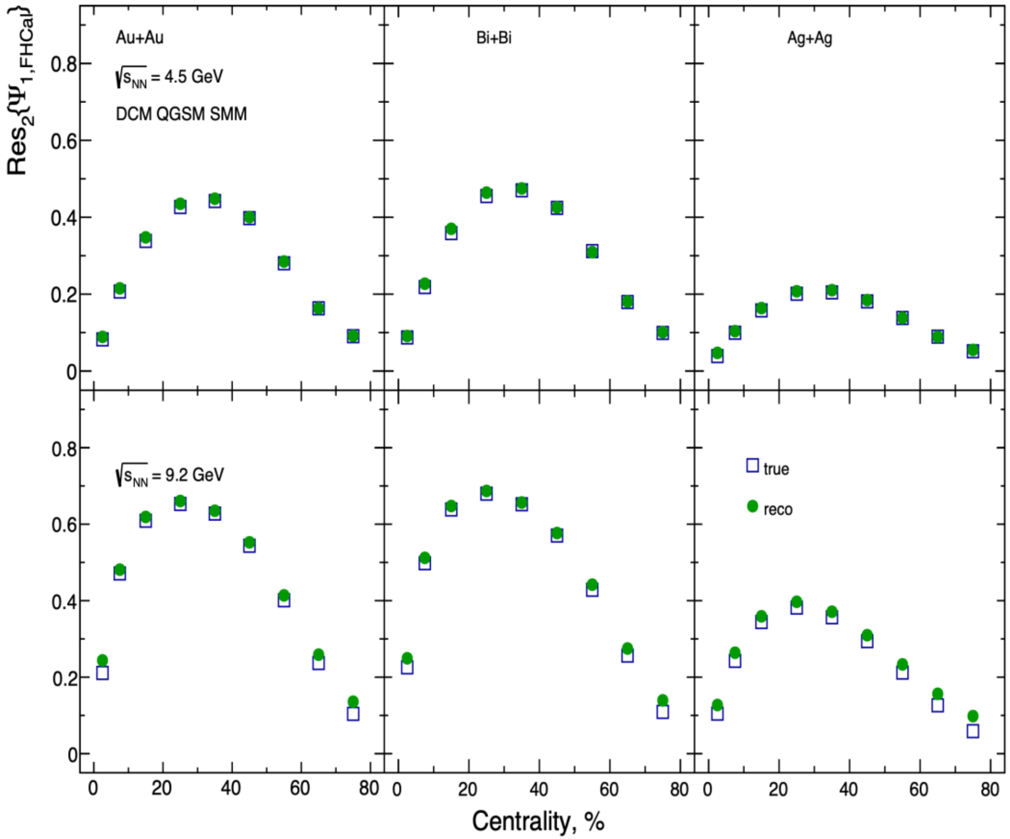
Performance of v_2 of pions and protons in MPD



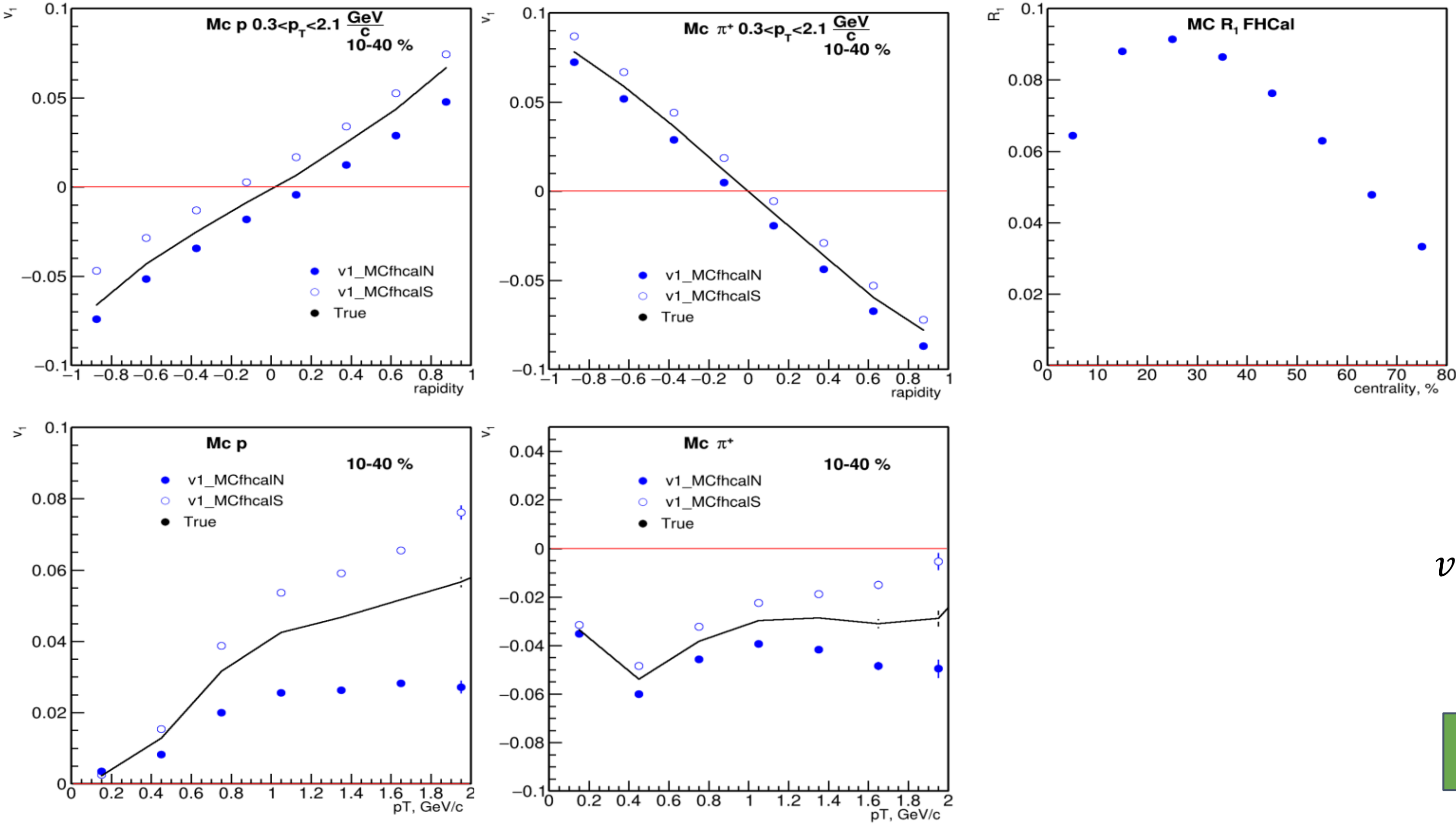
Reconstructed and generated v2 of pions and protons have a good agreement for all methods

Event Plane Resolution of $\Psi_{1,FHCal}$ for V_1 and V_2 measurements ($Bi+Bi, Au+Au, Ag+Ag$)





Difference between directed flow w.r.t. FHCal EP

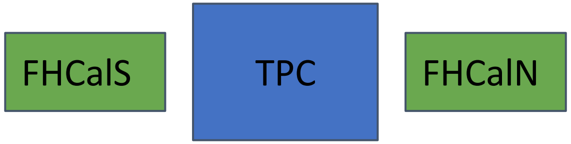


UrQMD, Bi+Bi, $\sqrt{s_{NN}}$=9.2 GeV
Production request 25

R_1 formed by all hadrons in the FHCal acceptance $|\eta| \in [2;5]$

$$u_1 = e^{i\phi}, Q_1 = \frac{1}{\sum w_k} \sum w_k u_{1,k}$$

$$v_1^{N,S} = 2\frac{\langle u_1 Q_1^{N,S*} \rangle}{\sqrt{2\langle Q_1^S Q_1^{N*} \rangle}} \equiv 2\frac{\langle u_1 Q_1^{N,S*} \rangle}{R_1}$$



Difference between v_1^N and v_1^S might be due to non-flow (momentum conservation)
Methods based on mixed harmonics must be employed to suppress this effect

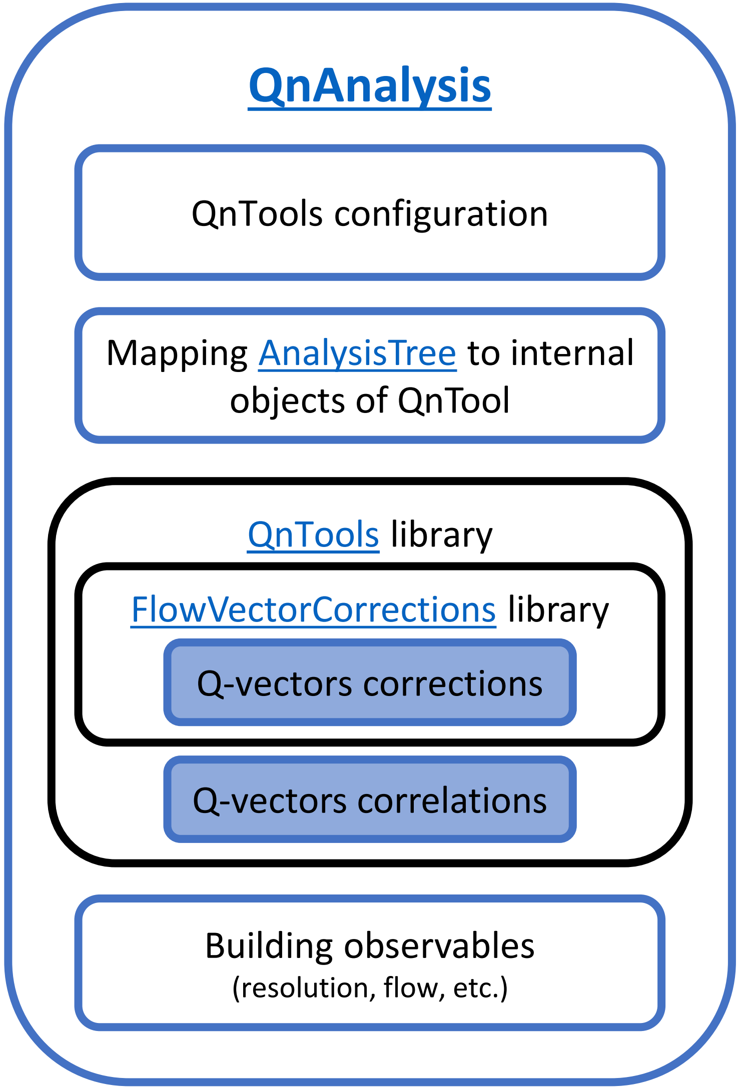
The QnAnalysis package

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

QnAnalysis requirements:
- ROOT ver. ≧ 6.20 (with MathMore library)
- C++17 compatible compiler
- CMake ver. ≧ 3.13

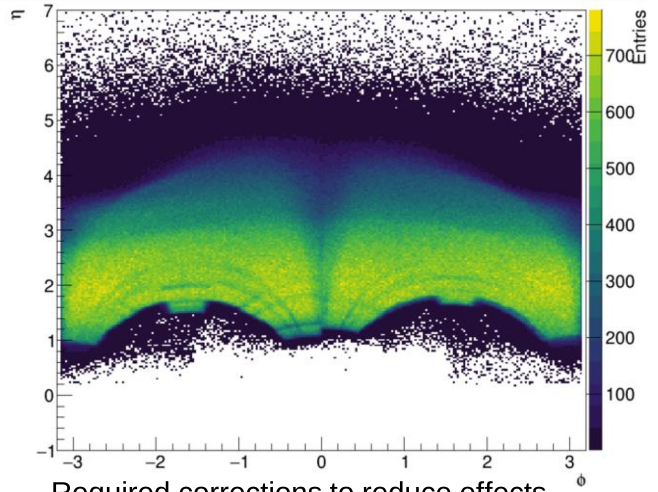
Can be easily installed on NICA cluster using ROOT and CMake modules

Git repository: https://github.com/HeavyIonAnalysis/QnAnalysis



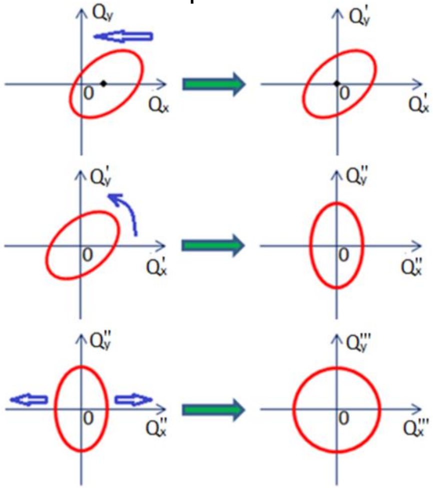
Azimuthal asymmetry of the BM@N acceptance

φ-η yield of protons

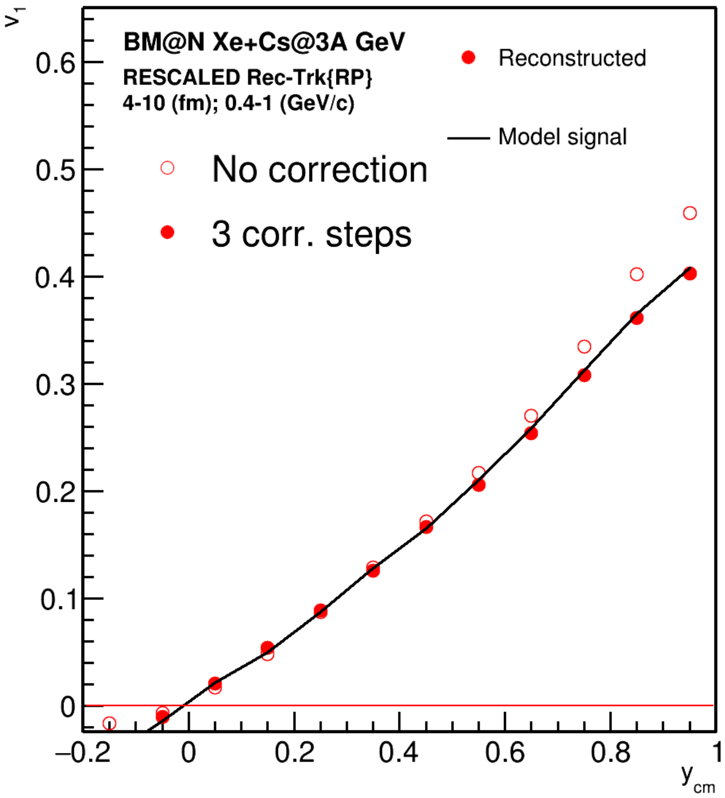


Required corrections to reduce effects of non-uniform azimuthal acceptance

1. Recentering
2. Twist
3. Rescaling

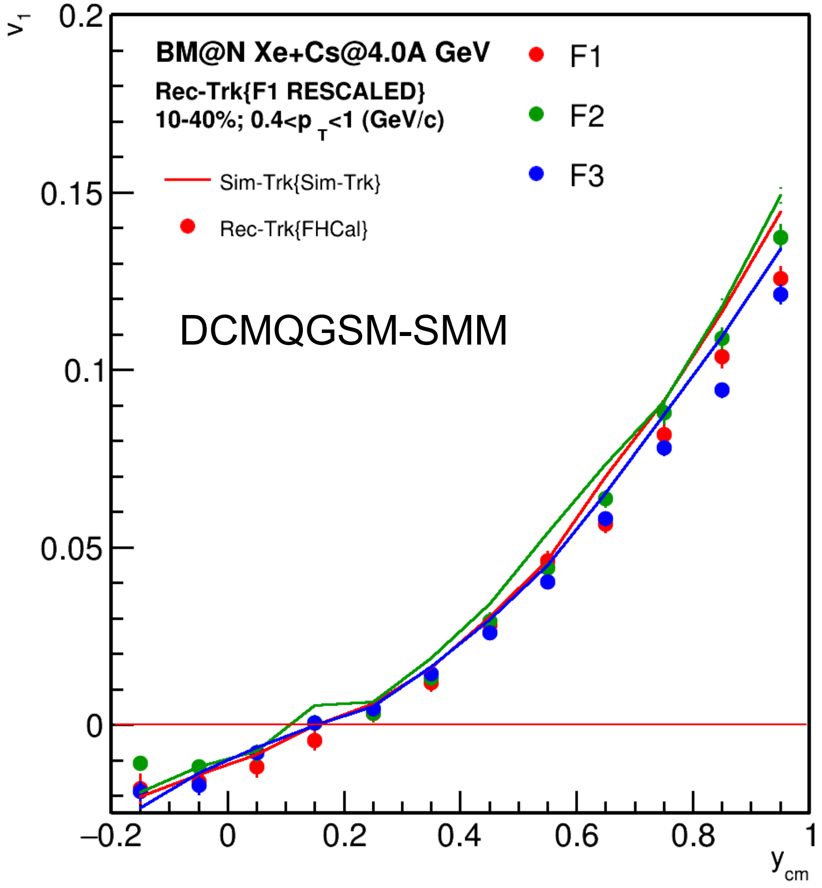


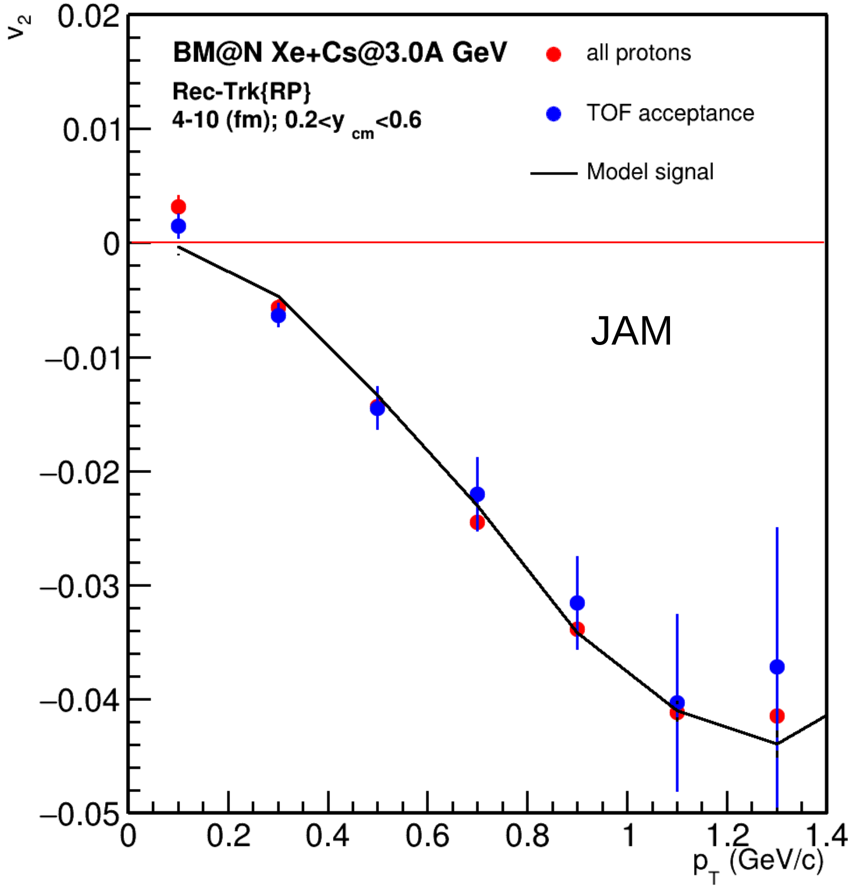
Corrections are based on method in:
I. Selyuzhenkov and S. Voloshin PRC77, 034904 (2008)



Better agreement after rescaling

BM@N performance study for the upcoming run



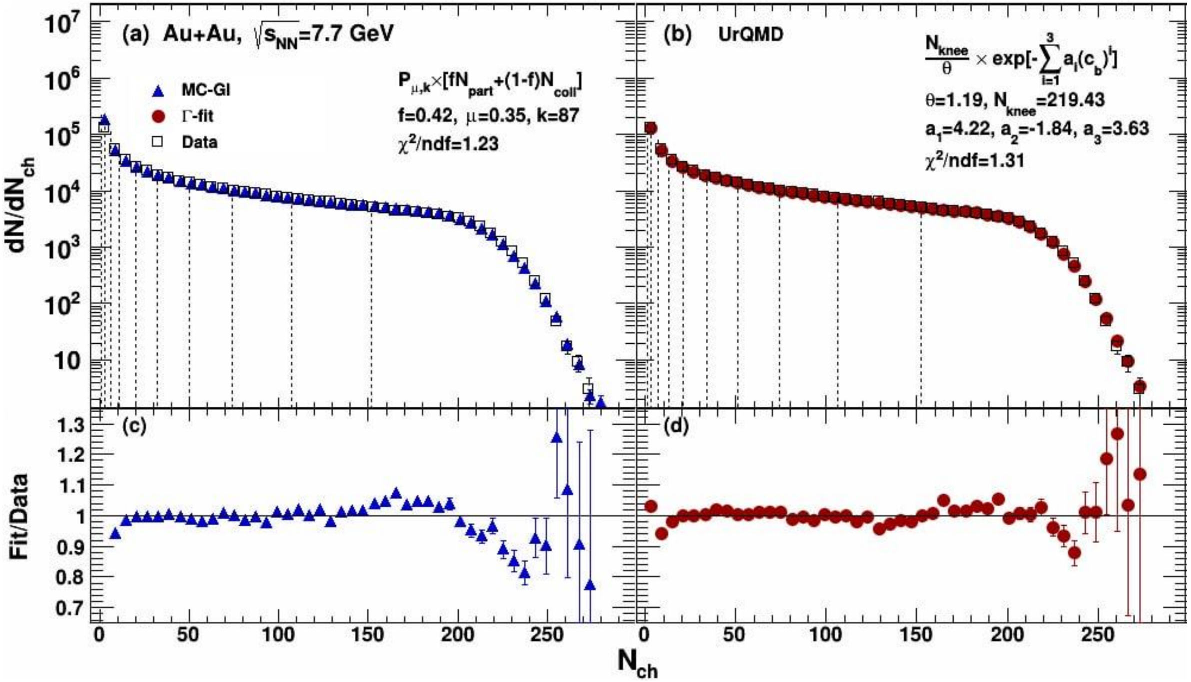


- The performance study was performed using QnAnalysis framework
- QnAnalysis framework will be verified one more time on BM@N data

Centrality determination based on charged particle multiplicity: MC-Glauber and Bayesian inversion method

1). Centrality Determination in Heavy-ion Collisions with MPD Detector at NICA, Acta Physica Polonica B Proceedings Supplement 14 (2021) 3, 503-506

2) Relating Charged Particle Multiplicity to Impact Parameter in Heavy-Ion Collisions at NICA Energies, Particles 4 (2021) 2, 275-287



Implementation in MPD:
https://github.com/FlowNICA/CentralityFramework
https://github.com/Dim23/GammaFit

Summary and outlook

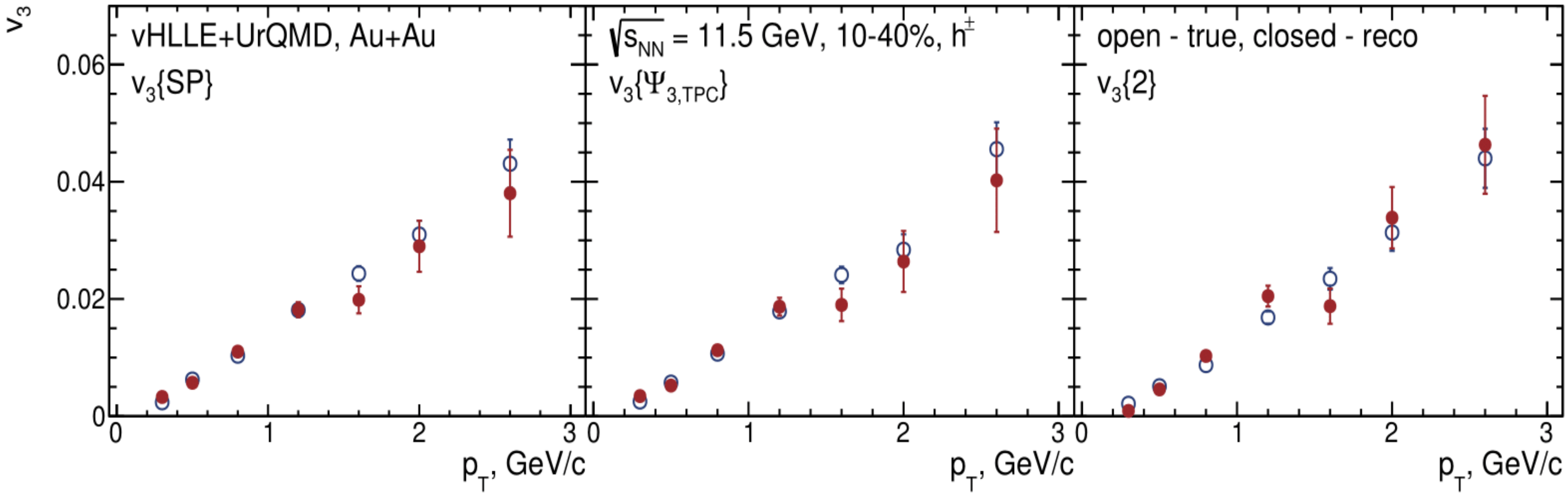
- **v_n at NICA energies shows strong energy dependence:**
  - At $\sqrt{s_{NN}}$=4.5 GeV v_2 from UrQMD, SMASH are in a good agreement with the experimental data
  - At $\sqrt{s_{NN}}\geq$7.7 GeV UrQMD, SMASH underestimate v_2 – need hybrid models with QGP phase
  - Detailed JAM model calculations for differential measurements of v_n at $\sqrt{s_{NN}}$ = 2.4-4.5 GeV
  - v_2 from cumulants of different orders
- **Comparison of methods for elliptic flow measurements using UrQMD and AMPT models:**
  - The differences between methods are well understood and could be attributed to non-flow and fluctuations
- **Feasibility study for anisotropic flow in MPD:**
  - v_n of identified charged hadrons: results from reconstructed and generated data are in a good agreement for all methods
- Small differences in v_n for 2 colliding systems (Au+Au, Bi+Bi) were observed as expected
- Programs for flow analysis are available for MPD collaboration:
  - Github repository: https://github.com/FlowNICA/CumulantFlow
  - QnAnalysis git link: https://github.com/HeavyIonAnalysis/QnAnalysis
  - AnalysisTree git link: https://github.com/HeavyIonAnalysis/AnalysisTree

Results for 2019-2022

3 Workshops on physics performance studies at FAIR and NICA, http://indico.oris.mephi.ru/event/221

28 presentations at conferences and workshops, 22 publications and 3 master diploma works

Triangular flow with MPD at NICA



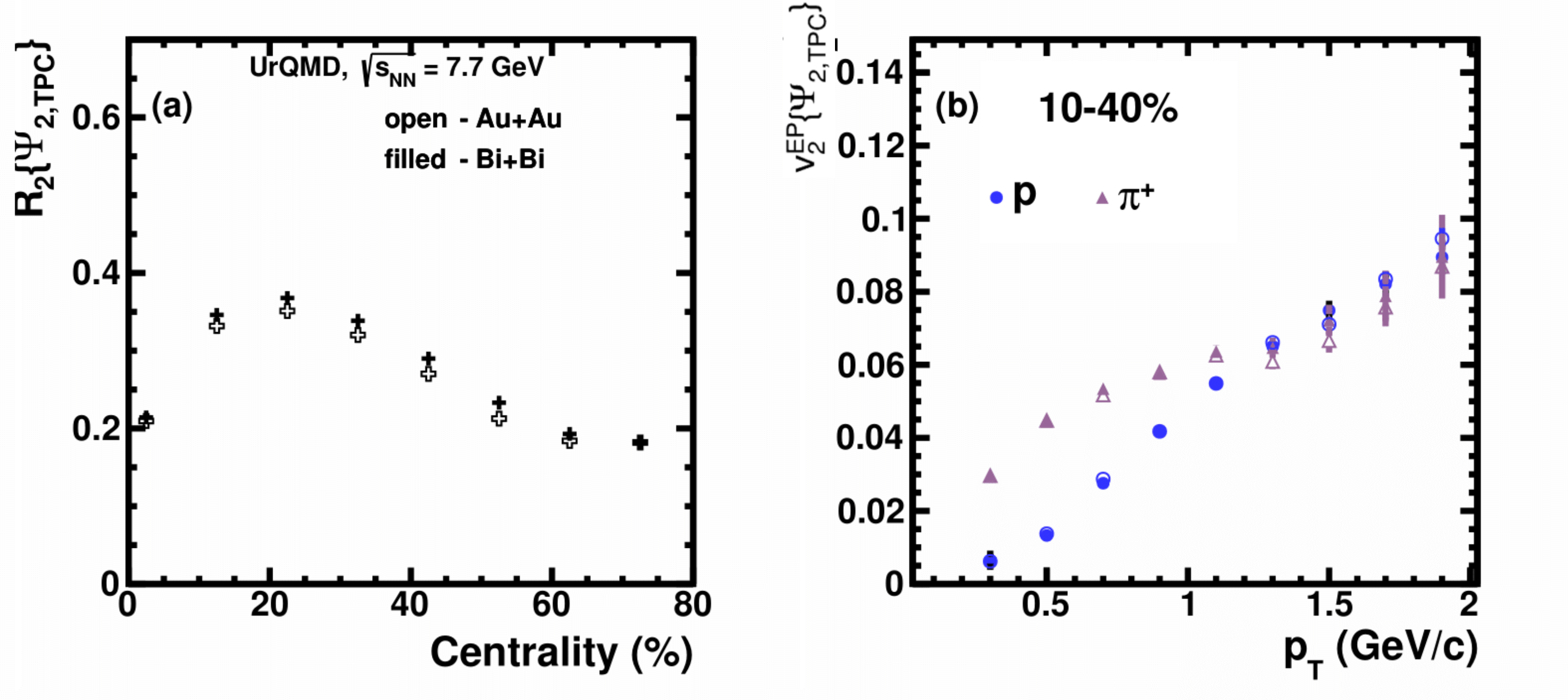
Models show that higher harmonic ripples are more sensitive to the existence of a QGP phase

In models, v_3 goes away when the QGP phase disappears????

15 M of reconstructed vHLLE + UrQMD events for Au+Au at 11.5 GeV

Au+Au vs. Bi+Bi collisions for MPD reconstructed data

- TPC event plane



- Expected small difference between two colliding systems

v_n of V0 particles: invariant mass fit method (Nikolay Geraksiev)

Data set:

- 25 million events, UrQMD 3.4 non-hydro, 11.0 GeV, minbias

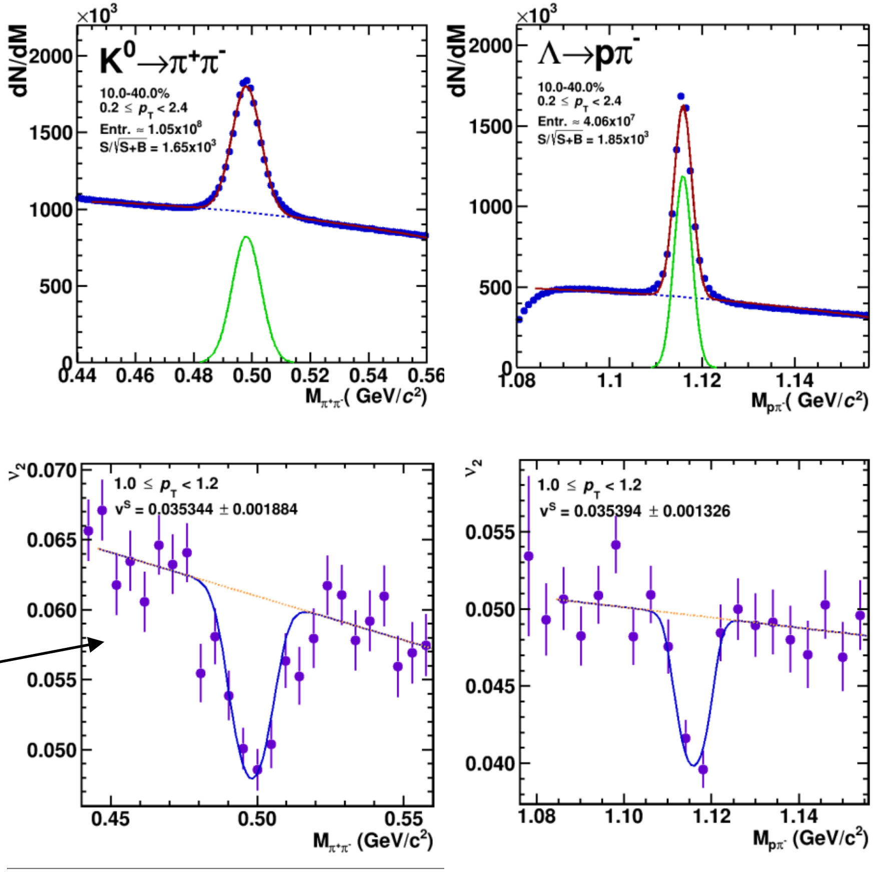
Geant4 simulation, full reconstruction with:

- TPCv7, TOFv7, FHCal

Centrality by TPC multiplicity, Event-plane method with FHCal

Particle decays reconstructed with MpdParticle realistic cuts
Differential flow signal extraction by bins in transverse momentum (or rapidity) with a simultaneous fit

$$v_2^{SB}(m_{inv},p_T) = v_2^S(p_T)\frac{N^S(m_{inv},p_T)}{N^{SB}(m_{inv},p_T)} + v_2^B(m_{inv},p_T)\frac{N^B(m_{inv},p_T)}{N^{SB}(m_{inv},p_T)}$$

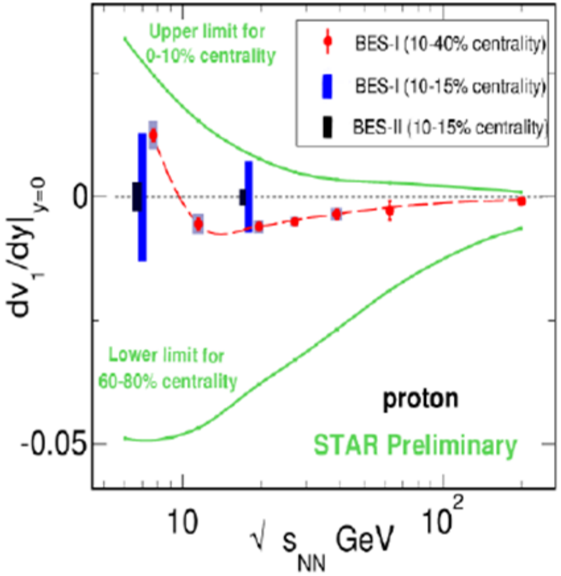


Outlook:

* Larger statistics with vHLLE (hydrodynamic evolution)
* Larger signal magnitude due to hydro (realistic input)
* Latest versions of detector geometry

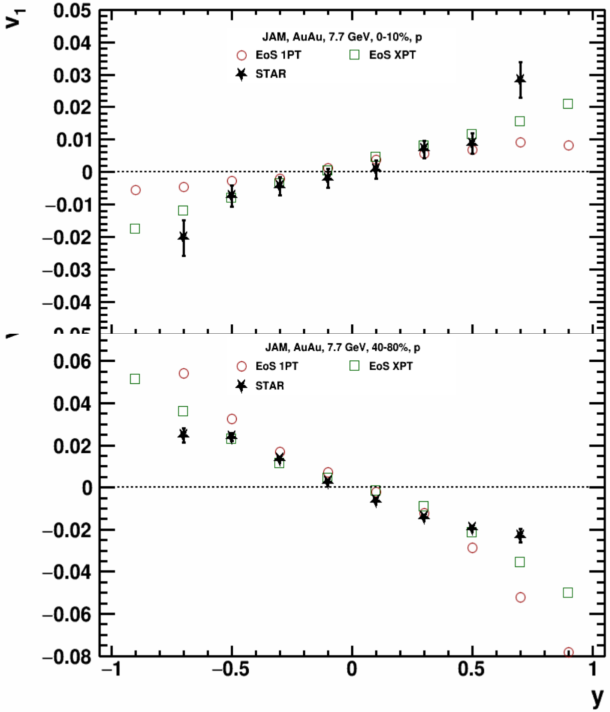
- Multi-variate analysis for reconstructed particle selection (TMVA)
- KFParticle

v_1 study at NICA energies



Slope dv_1/dy has non-monotonic behavior and strong centrality dependence

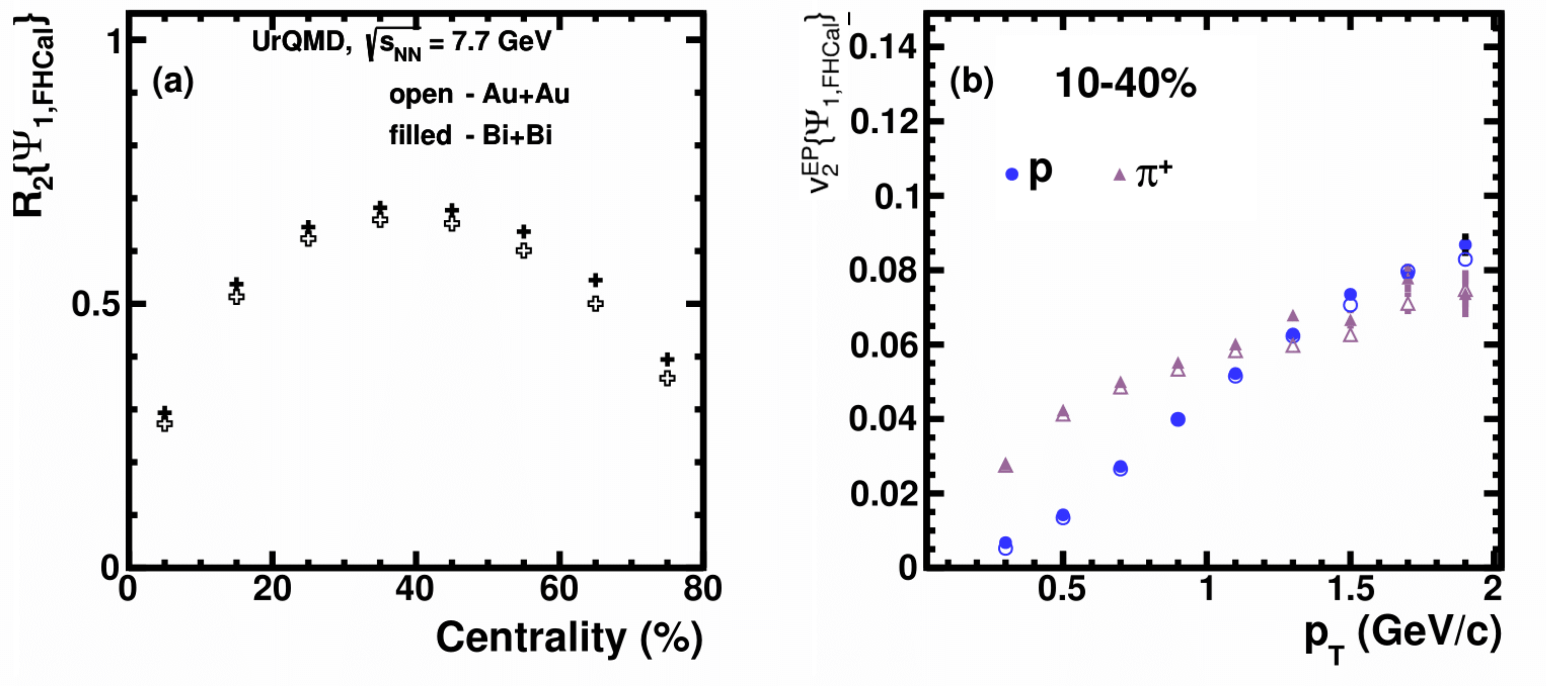
P. Parfenov, The Conference "RFBR Grants for NICA", Dubna (2020)



dv_1/dy slope changes dramatically with centrality for protons

Au+Au vs. Bi+Bi collisions for MPD reconstructed data

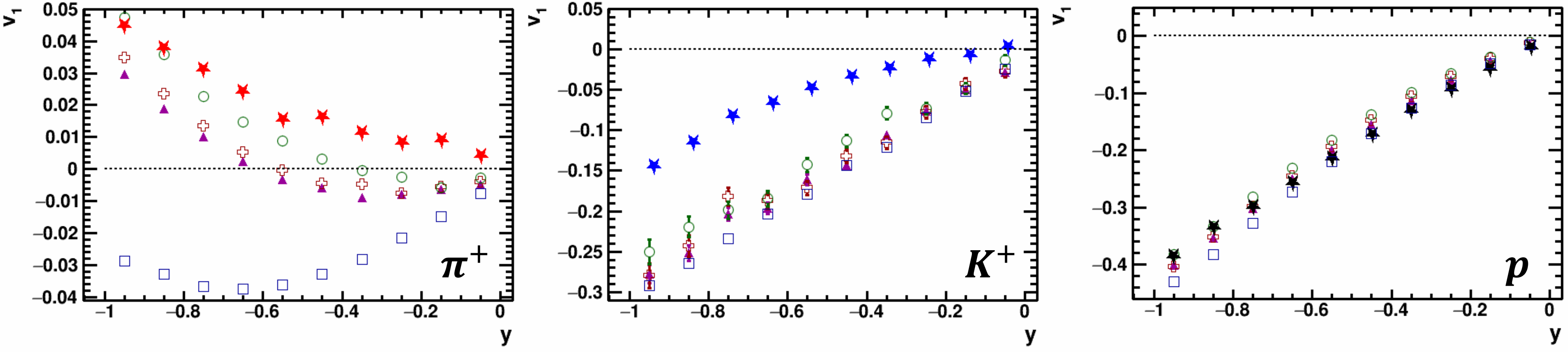
- FHCal event plane

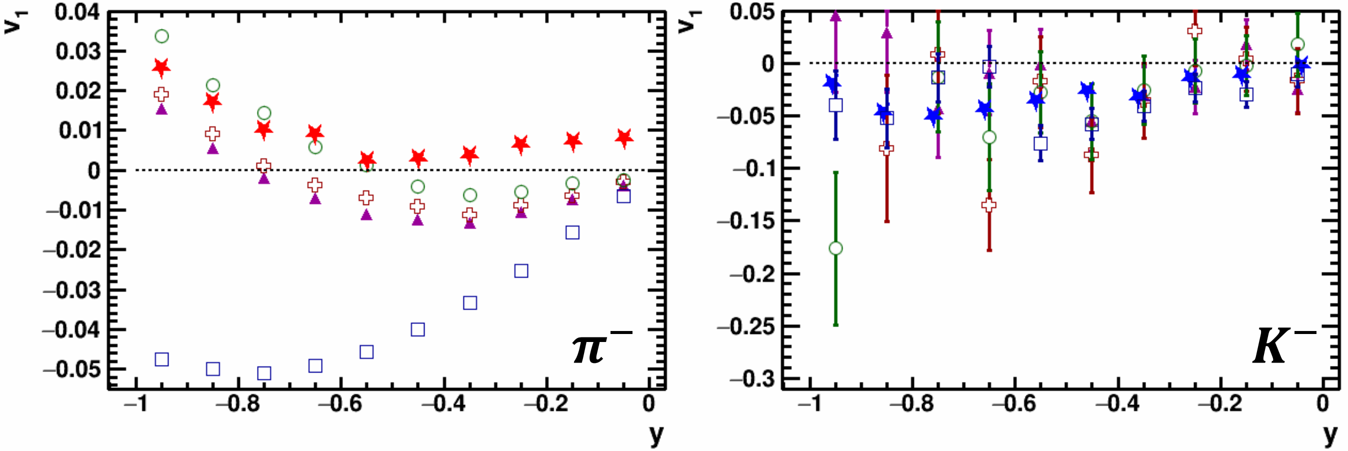


- Expected small difference between two colliding systems

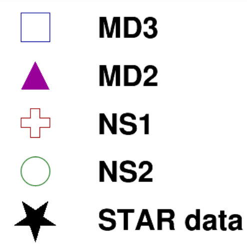
Back-up slides

$v_1(y)$ in Au+Au $\sqrt{s_{NN}}$=3 GeV: model vs. STAR data





JAM, Au+Au, 10-40% (4.6<b<9.3 fm)

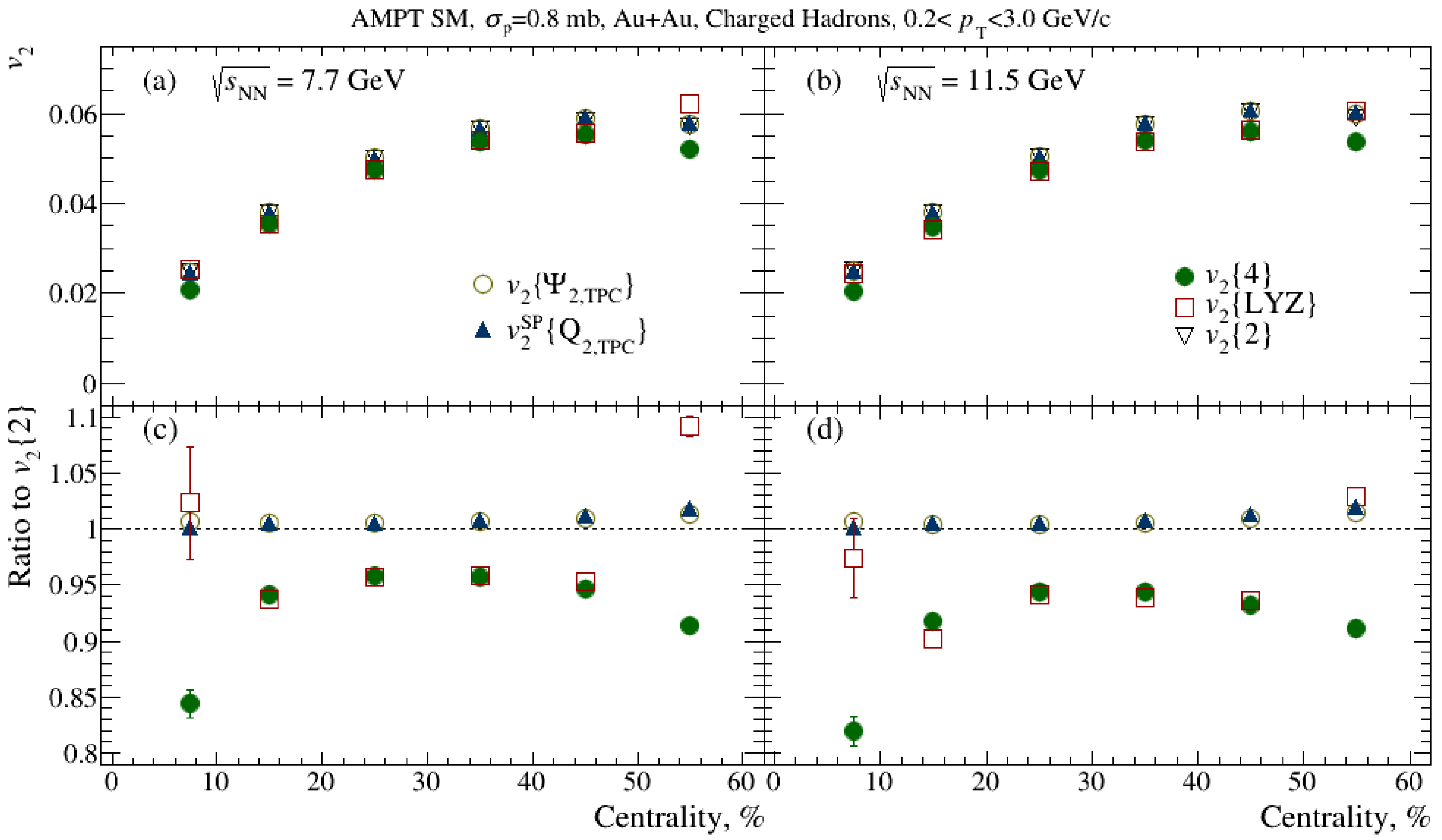


Kinematic cuts:
v_1(y) of $\pi^{\pm}$: 0.2 < pT < 1.6 GeV/c
v_1(y) of $K^{\pm}$: 0.4 < pT < 1.6 GeV/c
v_1(y) of p: 0.4 < pT < 2.0 GeV/c

JAM does not describe all particle species equally well
v_1 of pions is most sensitive to different EOS

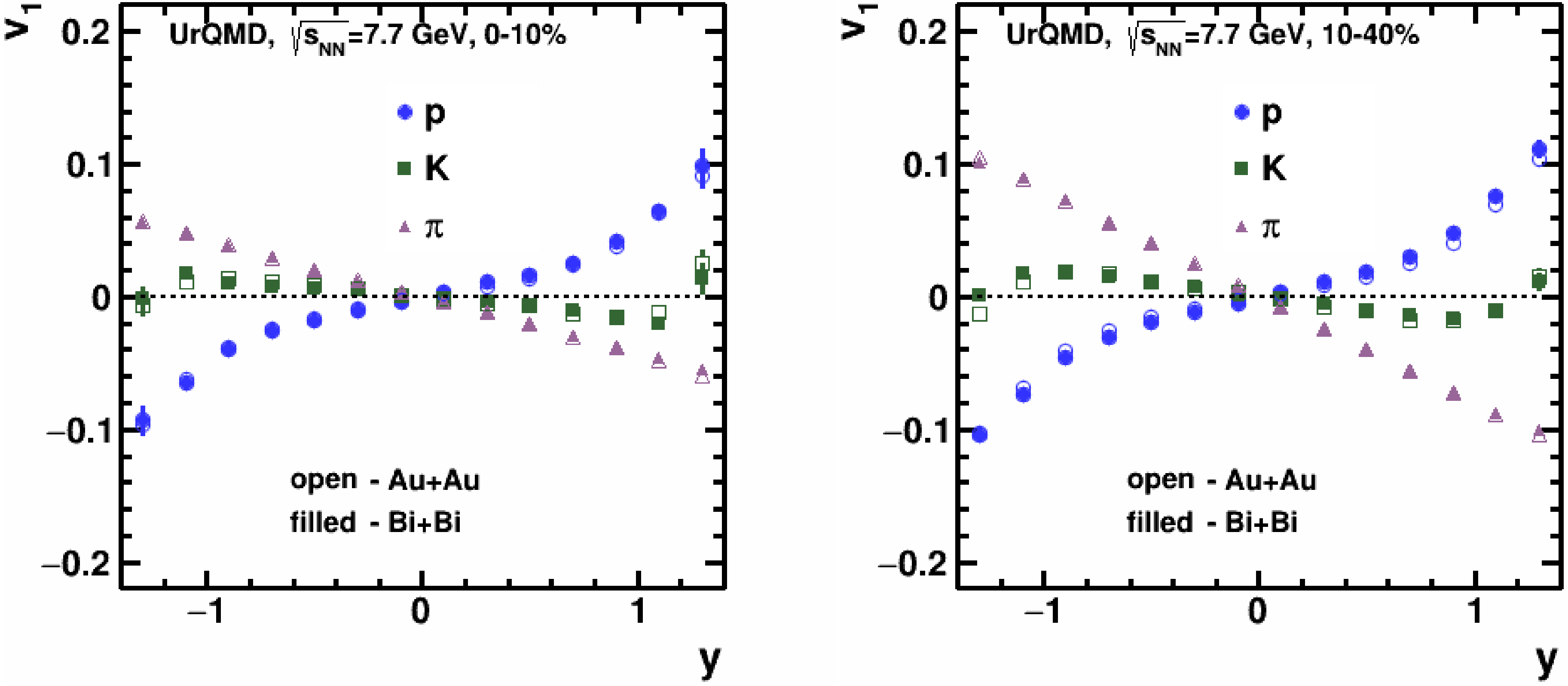
Experimental data points were taken from:
Mohamed Abdallah et al. [STAR Collaboration] 2108.00908 [nucl-ex]

Centrality dependence of v_2\{methods\}



$v_2\{4\} \approx v_2\{LYZ\}$, $v_2\{2\} \approx v_2\{SP\} \approx v_2\{\Psi_{2,TPC}\}$

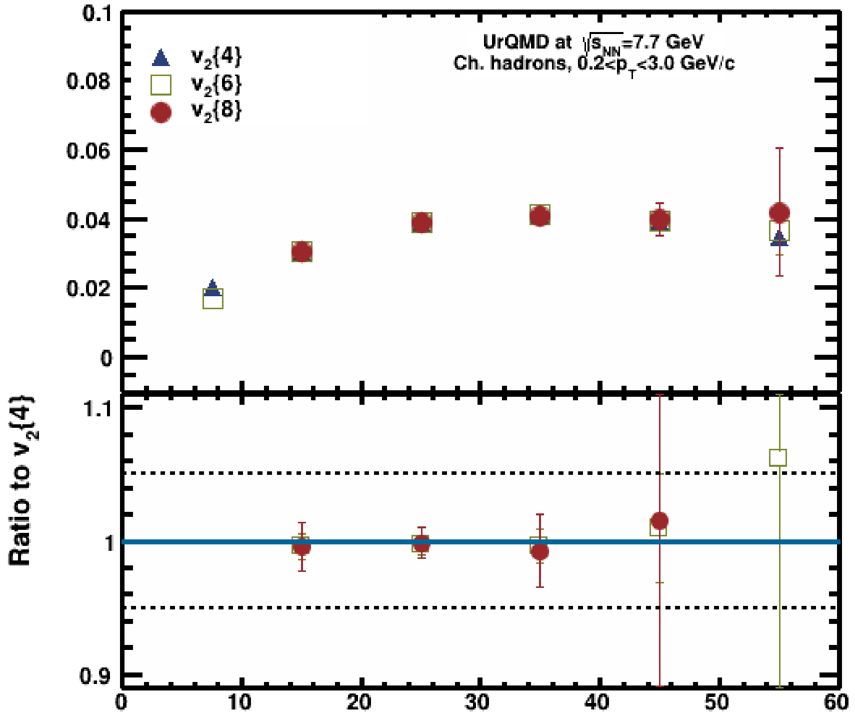
$v_1(y)$: Bi+Bi vs Au+Au



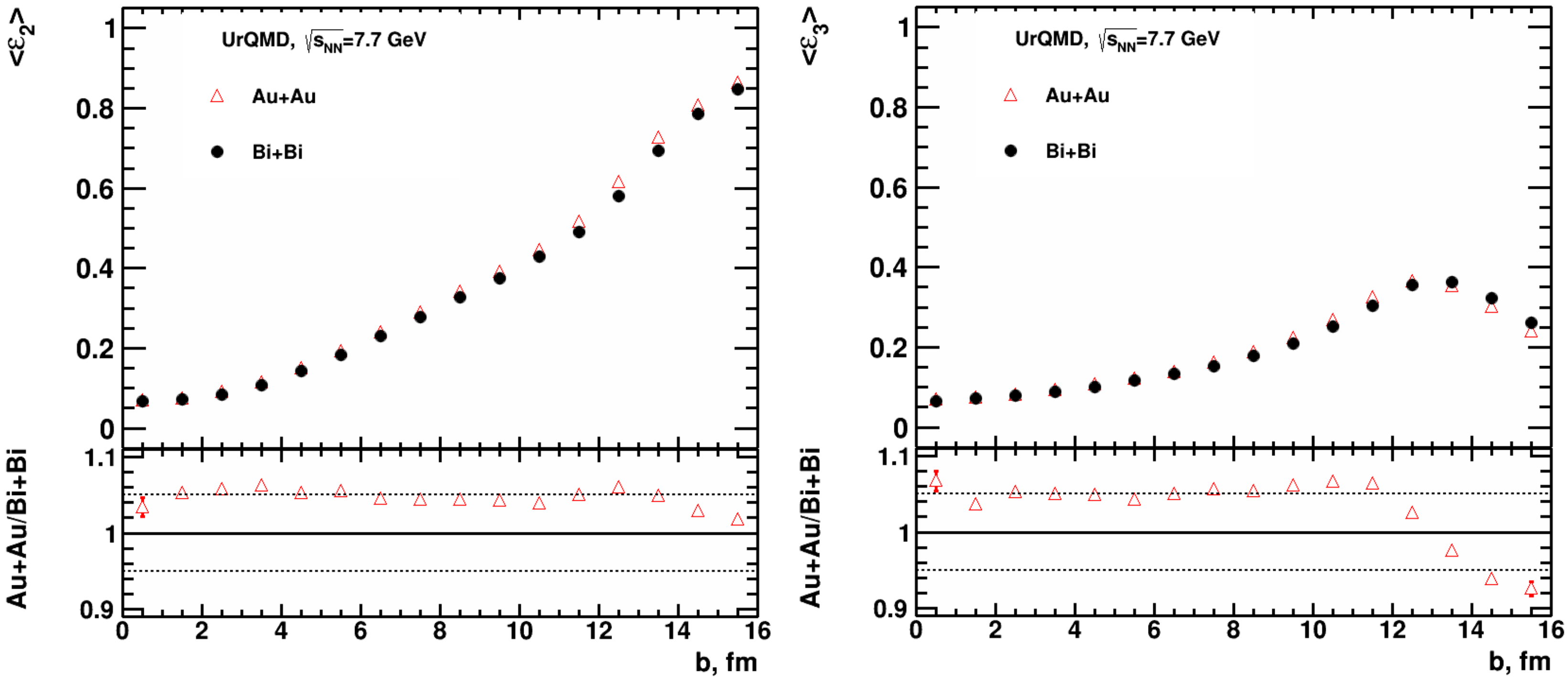
Expected small difference for v1 (y) for particles produced in Au+Au and Bi+Bi collisions.

Description of high-order Q-Cumulants

- **Higher order Q-Cumulants $v_2\{m\}$ (m=6,8):**
- (A. Bilandzic et al., Phys. Rev. C **89** (2014), 064904)
  - number of terms in "standalone" analytical expressions increases quickly with order of correlators
  - using recursive algorithms: calculate analytically higher-order correlators in terms of lower ones



Eccentricity: Bi+Bi vs. Au+Au



UrQMD model predicts small difference between ε_n of Au+Au and Bi+Bi