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

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With big help from Andrey Moshkin (JINR)

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For the MPD Collaboration

9th MPD Collaboration Meeting, JINR, Dubna, 25-27 April 2022

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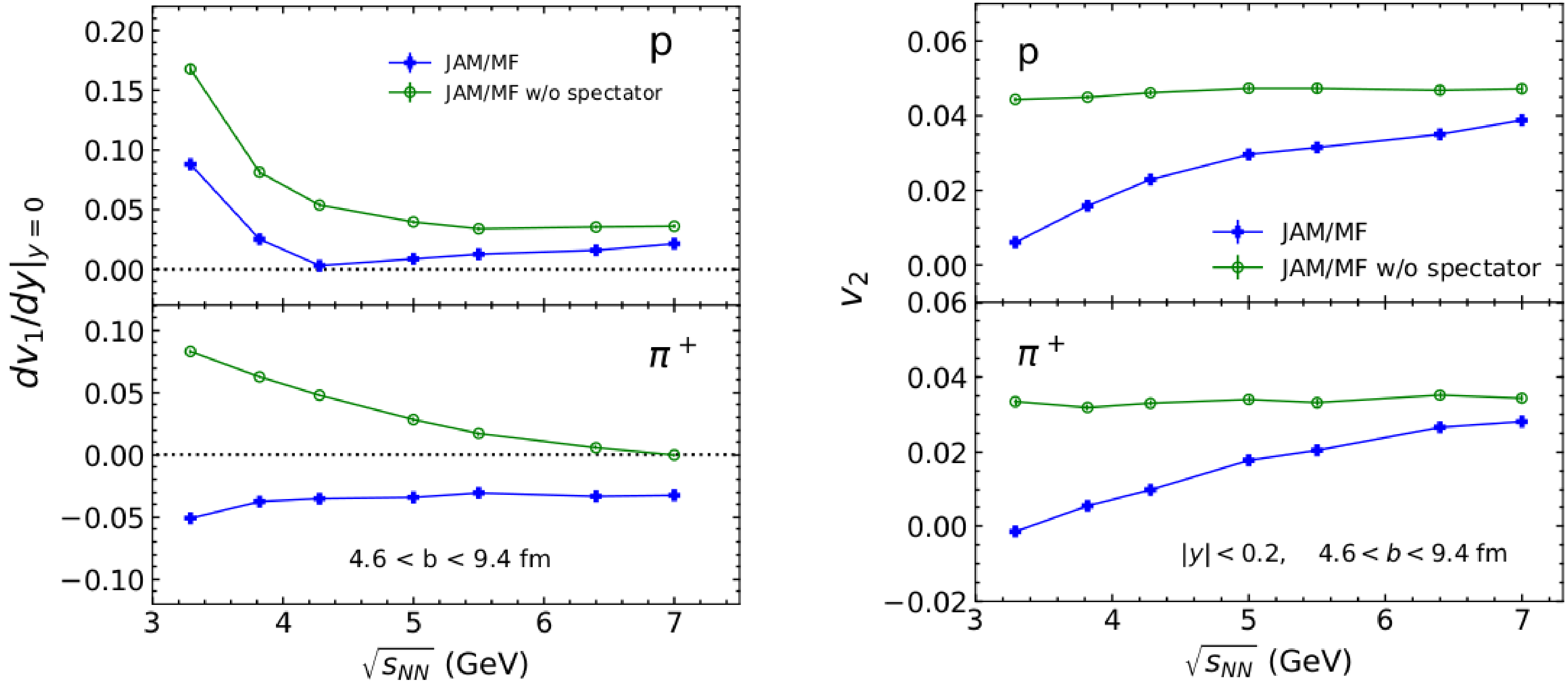
Anisotropic flow in Au+Au collisions at NICA energies

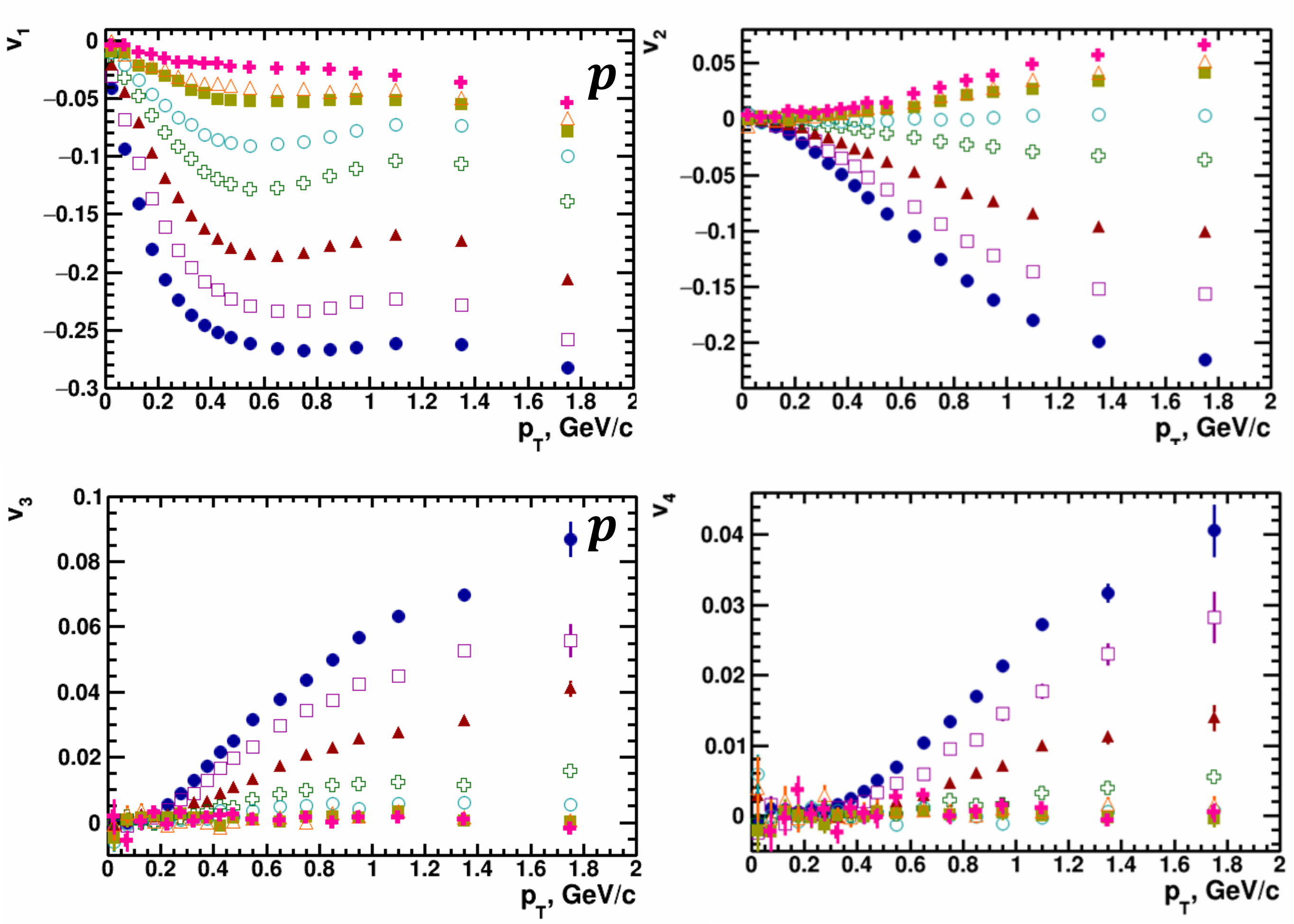
Phys. Rev. C 97, 064913 (2018)

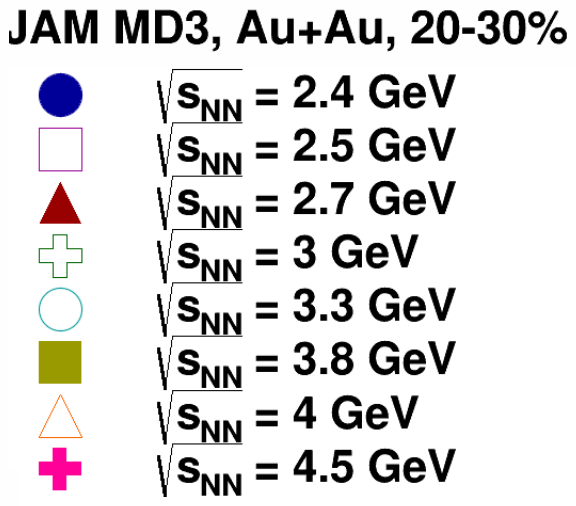


$$\frac{dN}{d\phi} \propto 1 + 2\sum_{n=1} \boldsymbol{v_n} \cos[n(\phi - \Psi_{RP})], \qquad v_n = \langle\cos[n(\phi - \Psi_{RP})]\rangle$$

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

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





Protons:

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

$V_{1,3}(y)$: 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**

See Peter Parfenov talk for other models (UrQMD, HSD, PHQMD, DCM-QGSM,.. , EOS and details

Anisotropic Flow at Nuclotron-NICA energies: Data vs Models - Plans

Anisotropic flow at NICA energies Models:

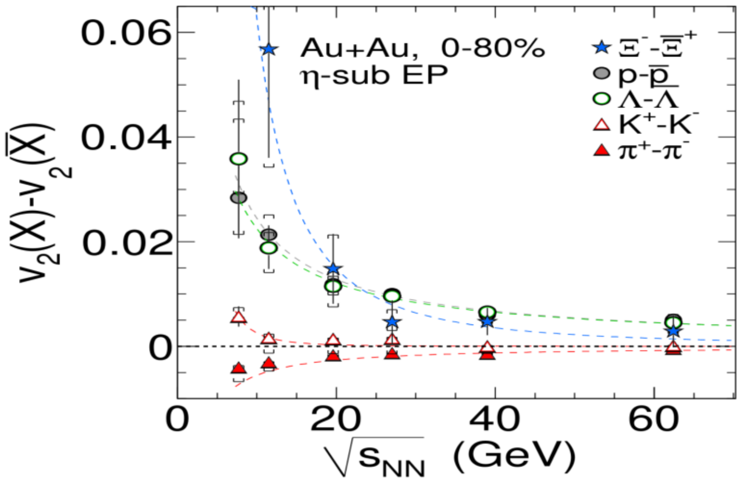
(1) String/Hadronic Cascade Models: UrQMD, HSD, SMASH, JAM, DCM-QGSM

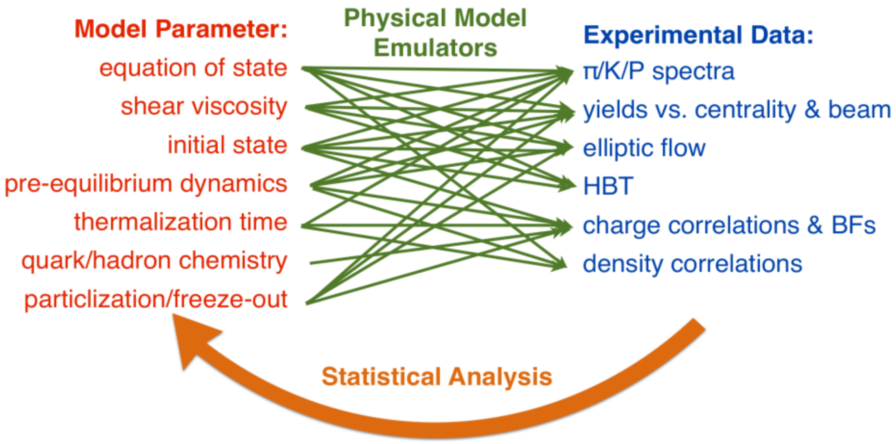
(2) Hybrid Models: viscous hydro+cascade (vHLLE+UrQMD, MUSIC+UrQMD,vHLLE+SMASH) и parton/string models (AMPT, PHSD и PHQMD)

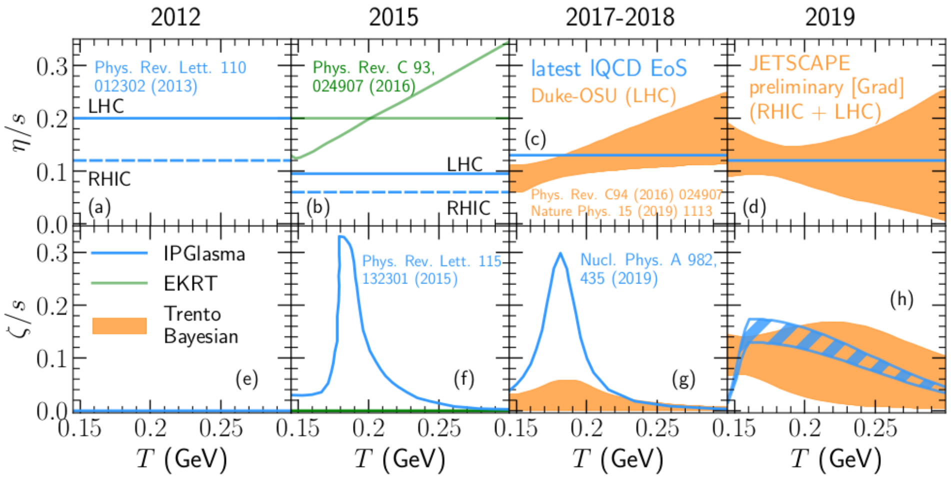
Goals:

- **Database of published vn results for comparison**
- **Hybrid model constructor**
- **Tools for a Bayesian analysis of Heavy Ion Collisions**

STAR Collaboration, Phys. Rev. C 88 (2013) 14902



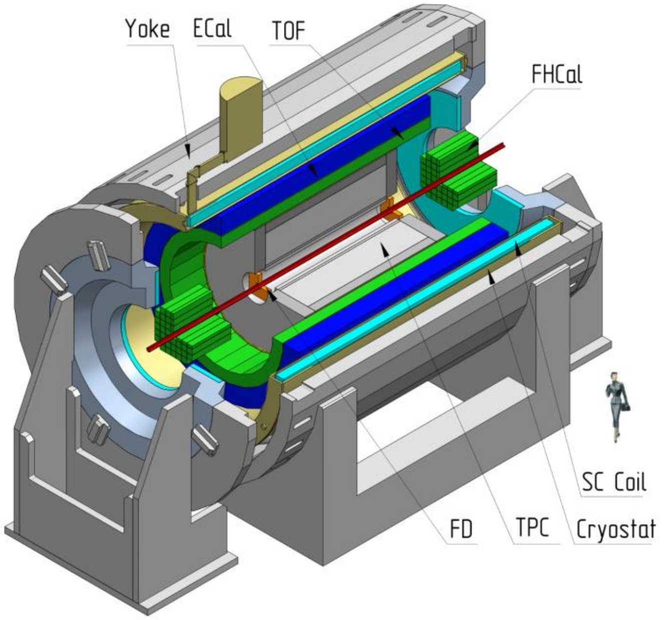




MPD Experiment at NICA

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



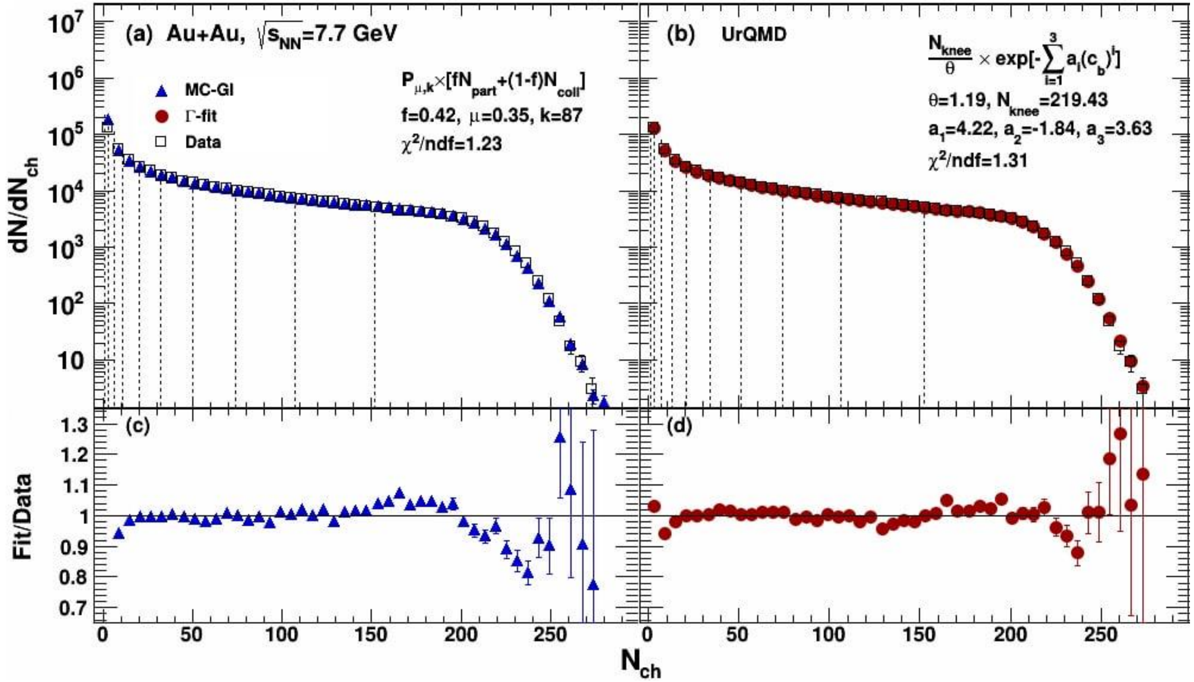
Multi-Purpose Detector (MPD) Stage 1

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

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

Event plane method using FHCal

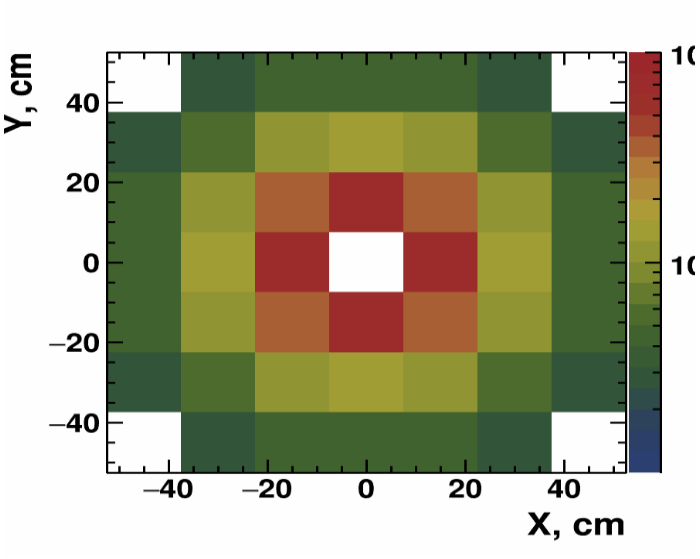
- Using v_1 of particles in FHCal to determine Q_n

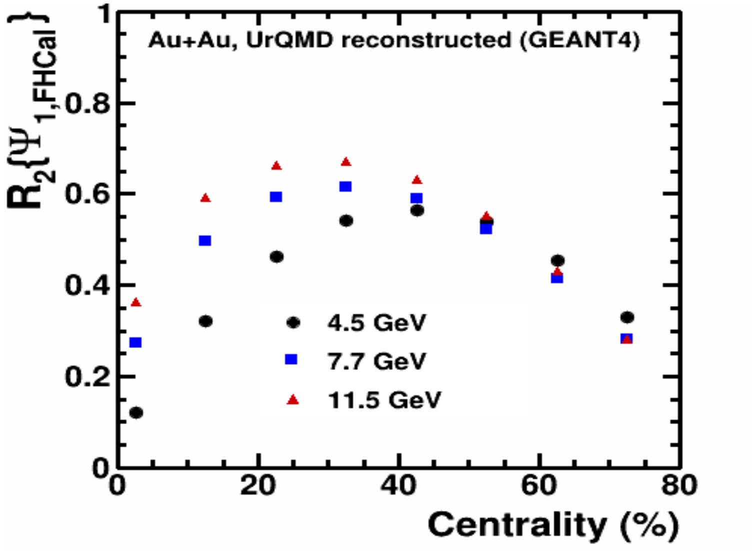
$$Q_1 = \frac{\sum_j E_i e^{i\phi_j}}{\sum_j E_j}, \quad \Psi_{1,\mathrm{FHCal}} = \tan^{-1}\left(\frac{Q_{1,y}}{Q_{1,x}}\right)$$

E – energy deposited in FHCal modules $(2 < |\eta| < 5)$

$$\mathrm{R}_2^{\mathrm{EP}}\{\Psi_{1,\mathrm{FHCal}}\} = \langle \cos[2(\Psi_{1,\mathrm{FHCal}} - \Psi_{\mathrm{RP}})] \rangle$$

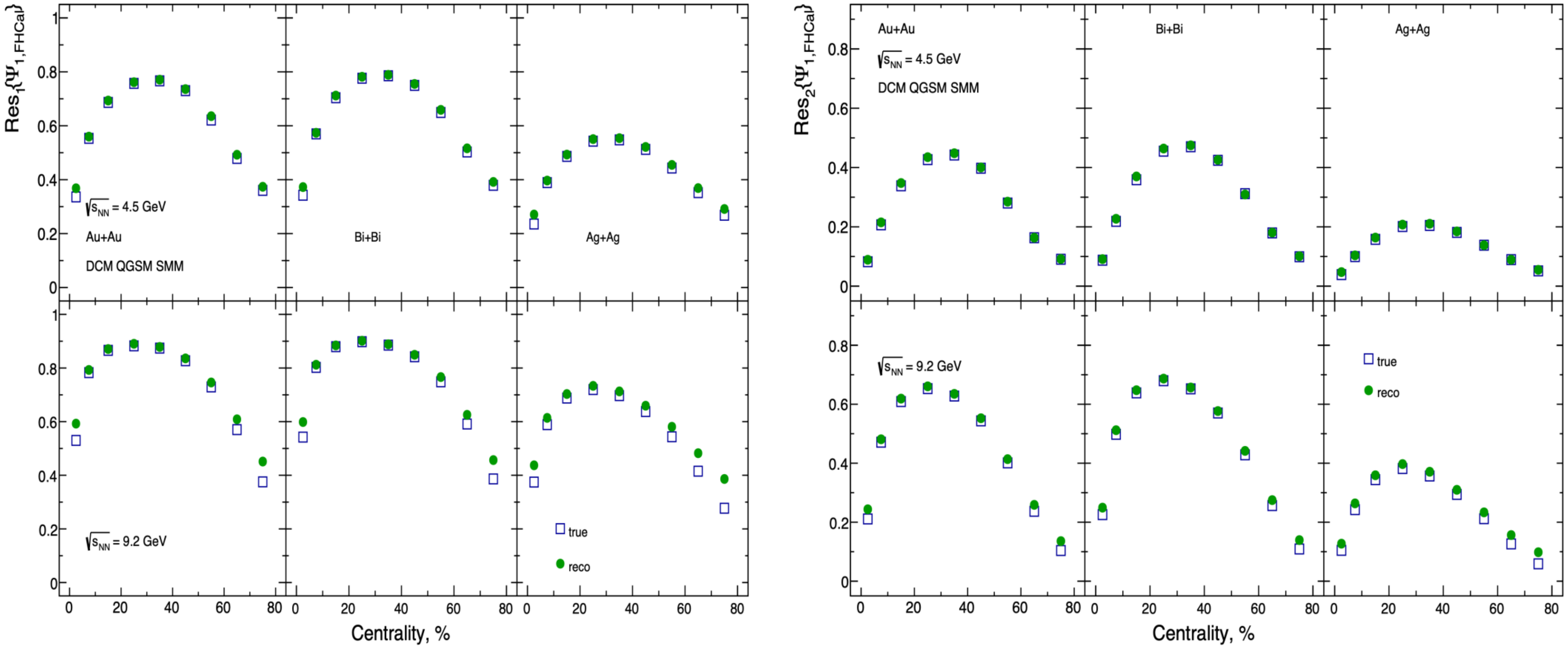
$$v_2^{\mathrm{EP}}\{\Psi_{1,\mathrm{FHCal}}\} = \frac{\langle \cos[2(\phi - \Psi_{1,\mathrm{FHCal}})] \rangle}{\mathrm{R}_2^{\mathrm{EP}}\{\Psi_{1,\mathrm{FHCal}}\}}$$



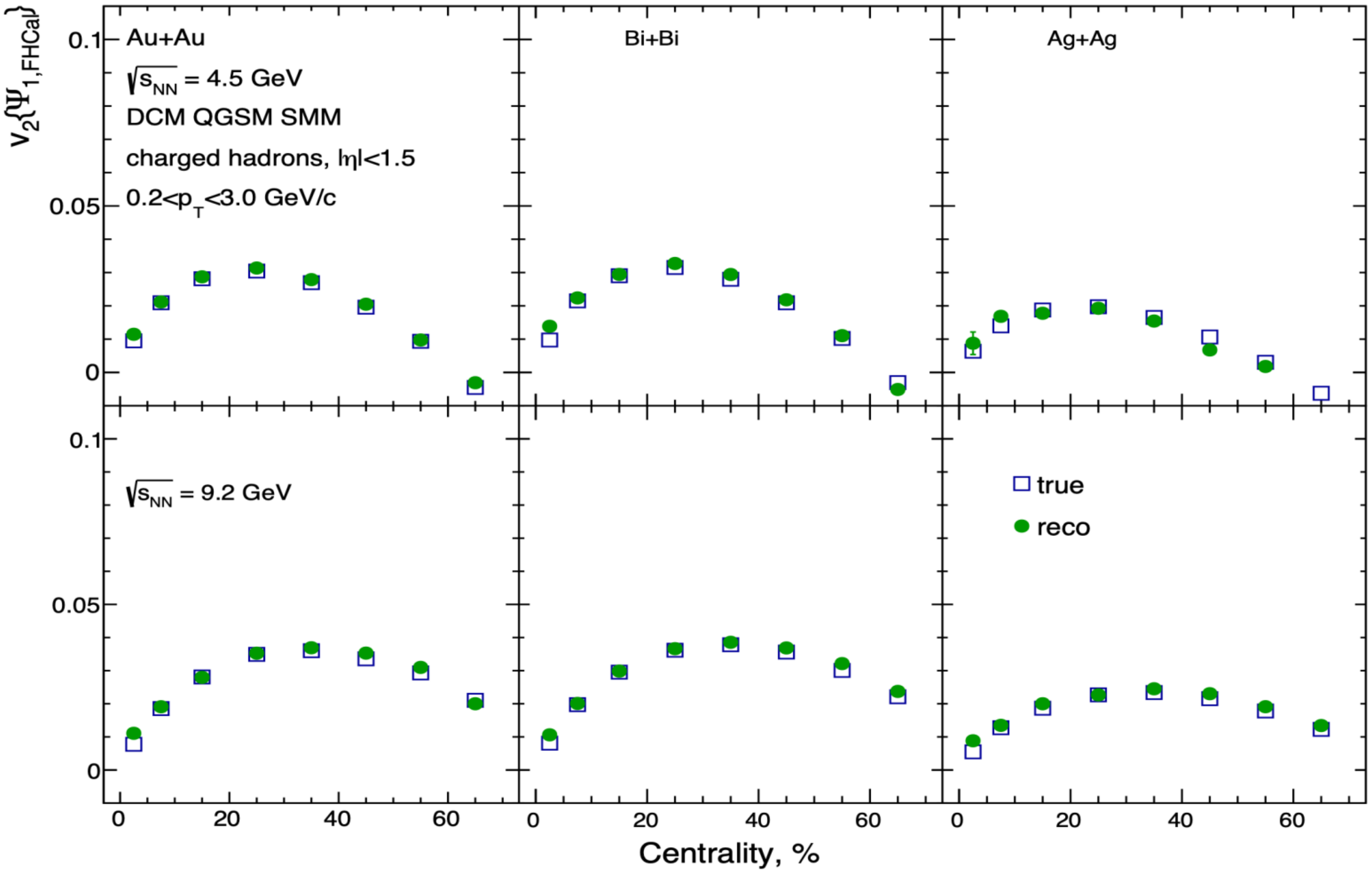


Recent results of $v_n\{\Psi_{1,FHCal}\}$: Particles **4** (2021), no.2, 146-158,
Acta Phys.Polon.Supp. 14 (2021) 3, 515-518, AIP Conf.Proc. 2377 (2021) 1, 030011

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



$v_2\{\Psi_{1,\mathrm{FHCal}}\}$



Flow measurements using TPC: Scalar product, Event-plane

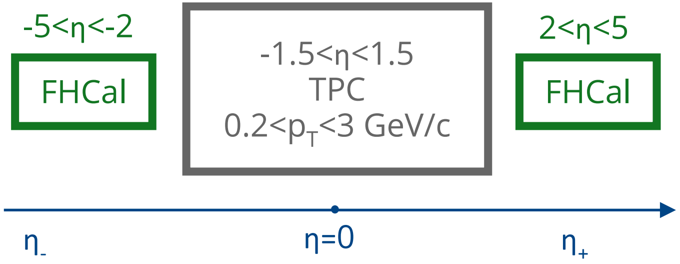
$$u_2 = \cos 2\phi + i \sin 2\phi = e^{2i\phi}$$

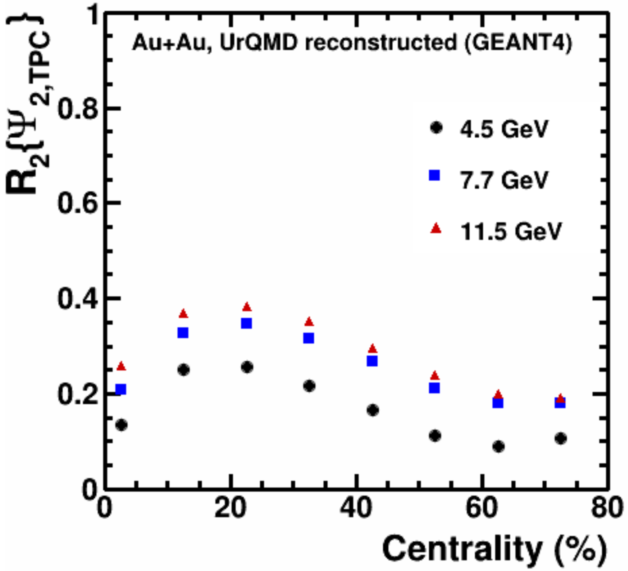
$$Q_2 = \sum_{j=1}^{M} \omega_j u_{2,j}, \; \Psi_{2,\mathrm{TPC}} = \frac{1}{2}\tan^{-1}\left(\frac{Q_{2,y}}{Q_{2,x}}\right)$$

- **Scalar product:** $v_2^{\mathrm{SP}}\{Q_{2,\mathrm{TPC}}\} = \frac{\langle u_{2,\eta\pm} Q^*_{2,\eta\mp}\rangle}{\sqrt{\langle Q_{2,\eta+} Q_{2,\eta-}\rangle}}$
- **TPC Event-plane:**

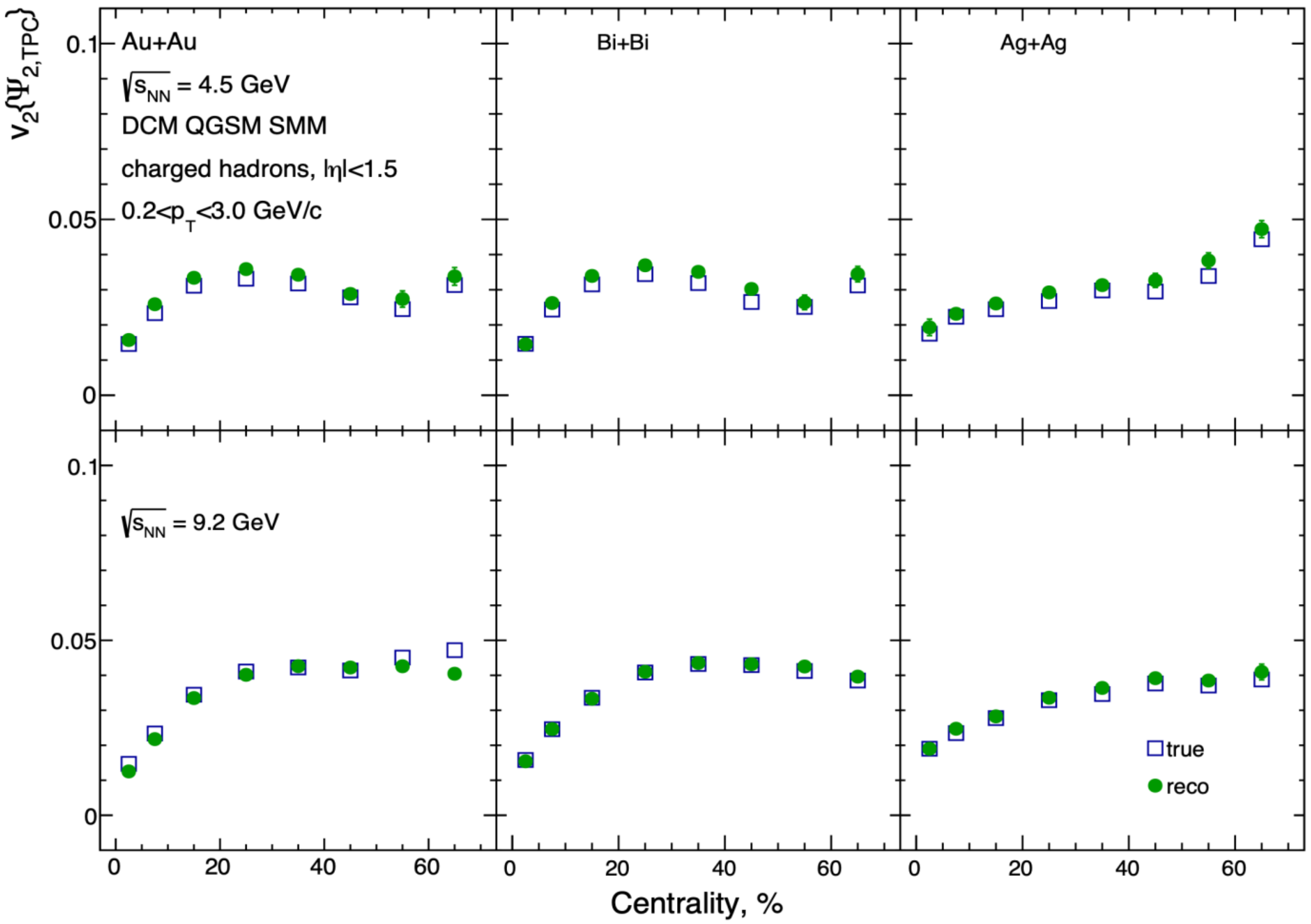
$$v_2^{\mathrm{EP}}\{\Psi_{2,\mathrm{TPC}}\} = \frac{\langle \cos\left[2(\phi_{\eta\pm} - \Psi_{2,\eta\mp})\right]\rangle}{\mathrm{R}_2^{\mathrm{EP}}\{\Psi_{2,\mathrm{TPC}}\}}$$

$$\mathrm{R}_2^{\mathrm{EP}}\{\Psi_{2,\mathrm{TPC}}\} = \sqrt{\langle \cos\left[2(\Psi_{2,\eta+} - \Psi_{2,\eta-})\right]\rangle}$$

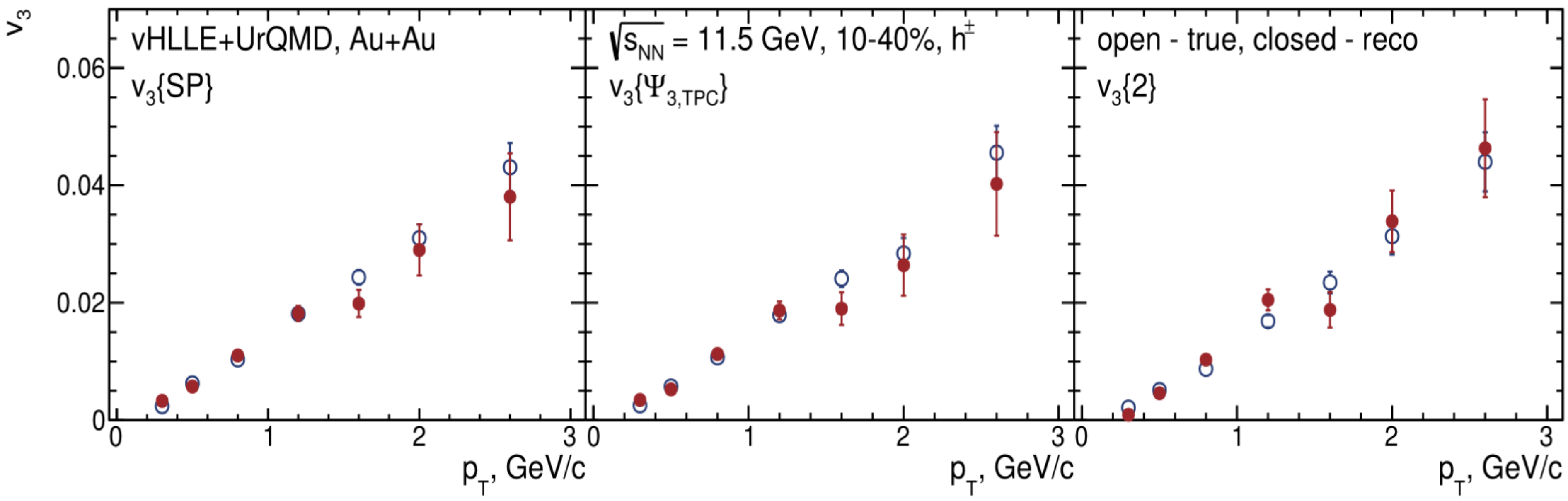




$v_2\{\Psi_{2,\mathrm{TPC}}\}$



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

Sensitivity of different methods to flow fluctuations

- Elliptic flow fluctuations: $\sigma_{v2}^2 = \langle v_2^2 \rangle - \langle v_2 \rangle^2$
- Assuming $\sigma_{v2} \ll \langle v_2 \rangle$ and a Gaussian form for flow fluctuations
- Fluctuations enhance $v_2\{2\}$ and suppress high-order **Q-Cumulants** compared to $\langle v_2 \rangle$:
- (S. A. Voloshin, A. M. Poskanzer, and R. Snellings, Landolt-Bornstein **23** (2010), 293)

$$v_2\{2\} \approx \langle v_2 \rangle + \frac{1}{2}\frac{\sigma_{v2}^2}{\langle v_2 \rangle}$$

$$v_2\{4\} \approx v_2\{6\} \approx v_2\{8\} \approx v_2\{\mathrm{LYZ}\} \approx \langle v_2 \rangle - \frac{1}{2}\frac{\sigma_{v_2}^2}{\langle v_2 \rangle}$$

- **TPC EP method**: (M. Luzum et al., Phys. Rev. C **87** (2013) 4, 044907)

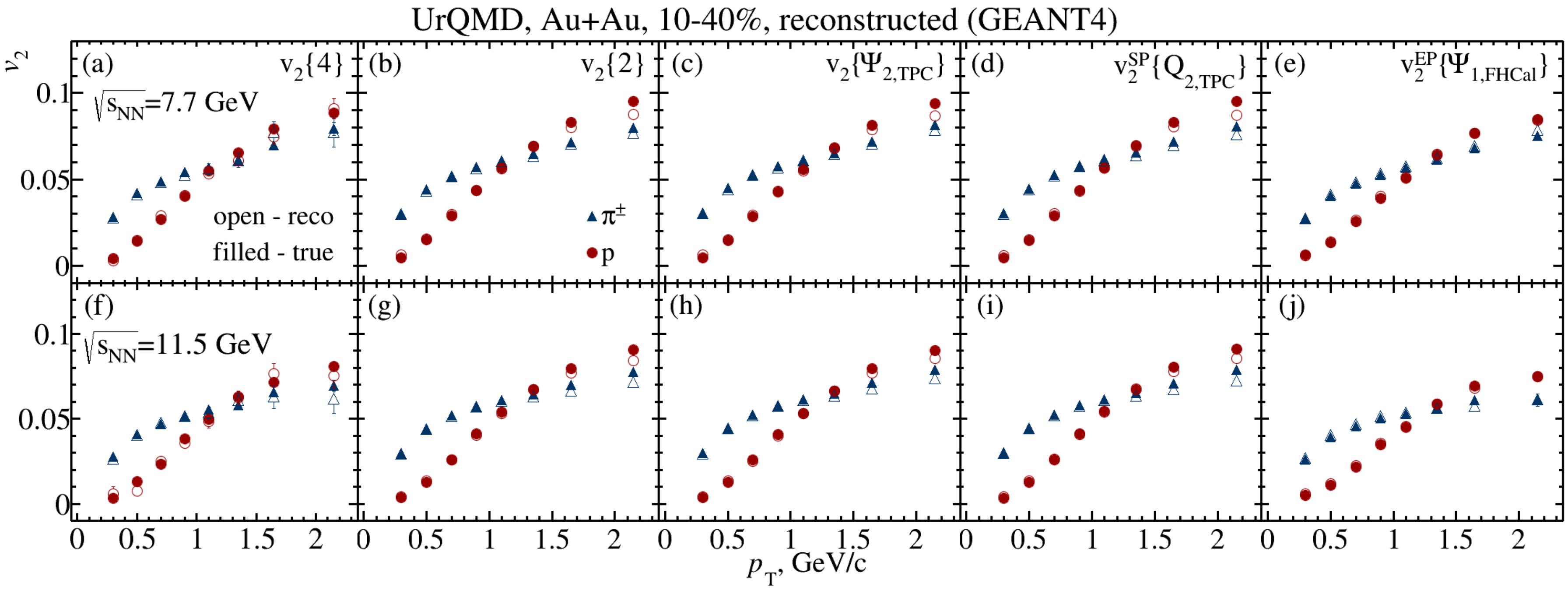
$$\langle v_2 \rangle \leq v_2^{\mathrm{EP}}\{\Psi_{2,\mathrm{TPC}}\} \leq \sqrt{\langle v_2^2 \rangle} \approx \langle v_2 \rangle + \frac{1}{2}\frac{\sigma_{v2}^2}{\langle v_2 \rangle}$$

- **Scalar product**:

$$v_2^{SP}\{Q_{2,\mathrm{TPC}}\} \approx \langle v_2 \rangle + \frac{1}{2}\frac{\sigma_{v2}^2}{\langle v_2 \rangle}$$

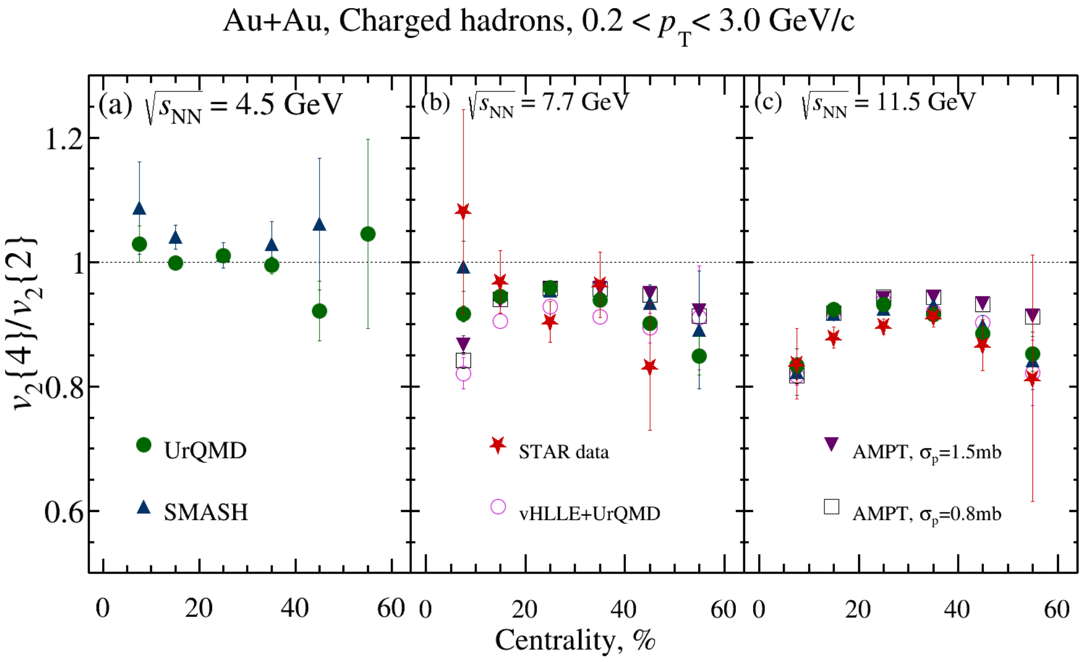
See Vinh Ba Luong presentation

Performance of v_2 of pions and protons in MPD



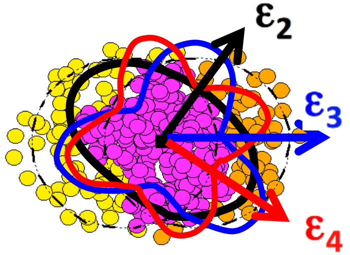
Reconstructed and generated v2 of pions and protons have a good agreement for all methods

Relative flow fluctuations of charged hadrons



STAR data: Phys.Rev.C **86**, 054908 (2012)
After quality cuts, 0-80%: 4M at 7.7 GeV, 11M at 11.5 GeV

- 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?



See Vinh Ba Luong presentation

$v_n\{2k\}$ (k=1,...,5) from JAM model

Group members:
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- **For the first time $v_n\{10\}$** $\quad v_n\{10\} = \sqrt[10]{\frac{1}{456} c_n\{10\}}$
- **$v_n\{2k\}$ (k=1,…,5) cumulant's statistical uncertainties are calculated analytically using the data:** **Phys. Rev. C 104 (2021) 034906, arXiv:2104.00588 [nucl-th].**
- **First time introduced a new (second) hydrodynamics probe that includes $v_2\{10\}$**
  - **First hydrodynamics probe:** $\frac{v_2\{6\} - v_2\{8\}}{v_2\{4\} - v_2\{6\}} = \frac{1}{11}$
  - **Second hydrodynamics probe:** $\frac{v_2\{8\} - v_2\{10\}}{v_2\{6\} - v_2\{8\}} = \frac{3}{19}$

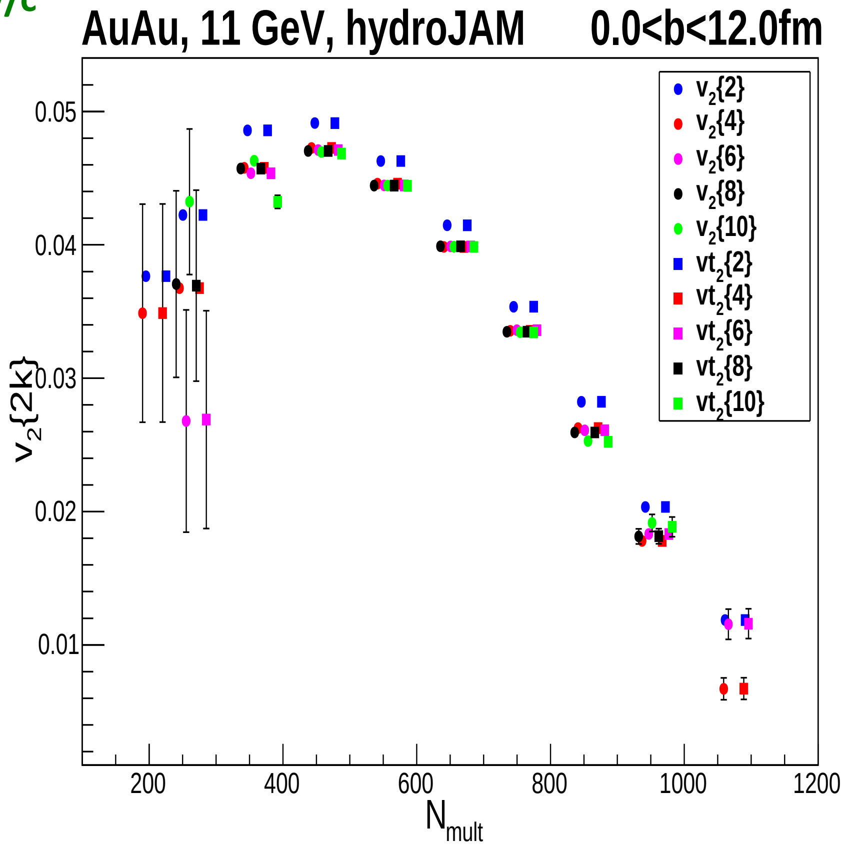
- **Codes for both, with and without efficiency corrections are developed**
- **Q-cumulants technique is applied as it is enable very fast calculations**
- Difficulties when flow magnitude, or particle multiplicity is too small

v_2 from cumulants of different orders - NICA

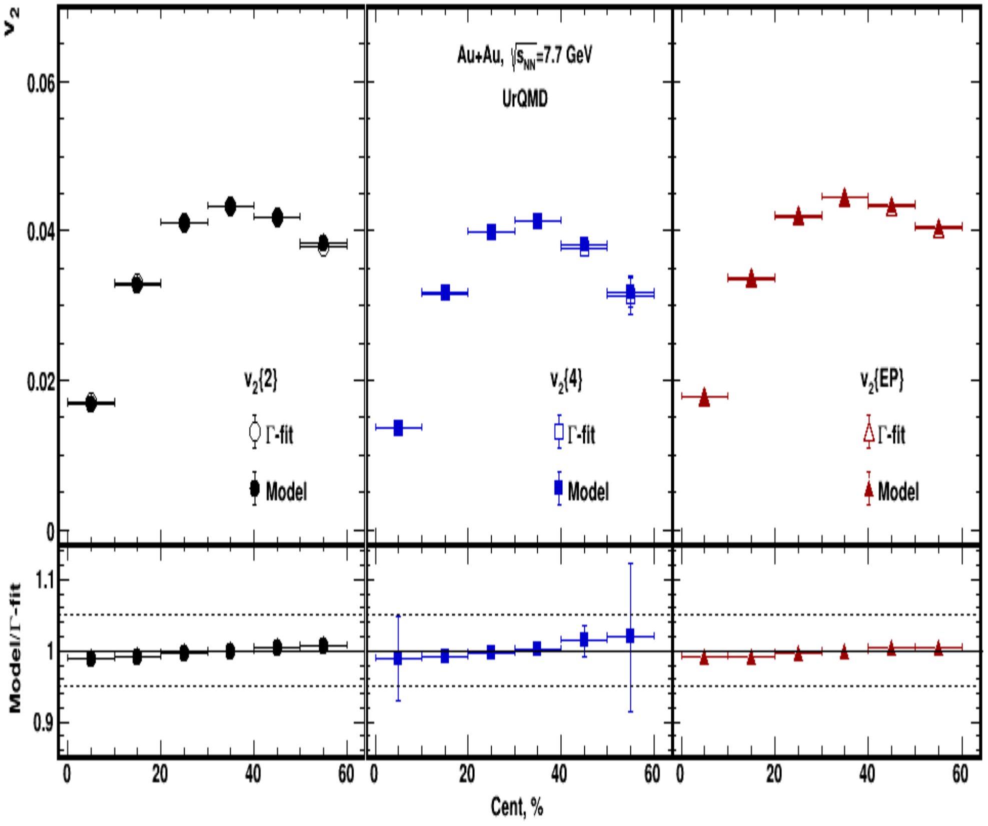
✧ AuAu collisions at $\sqrt{s_{NN}}$ = 11.0 GeV

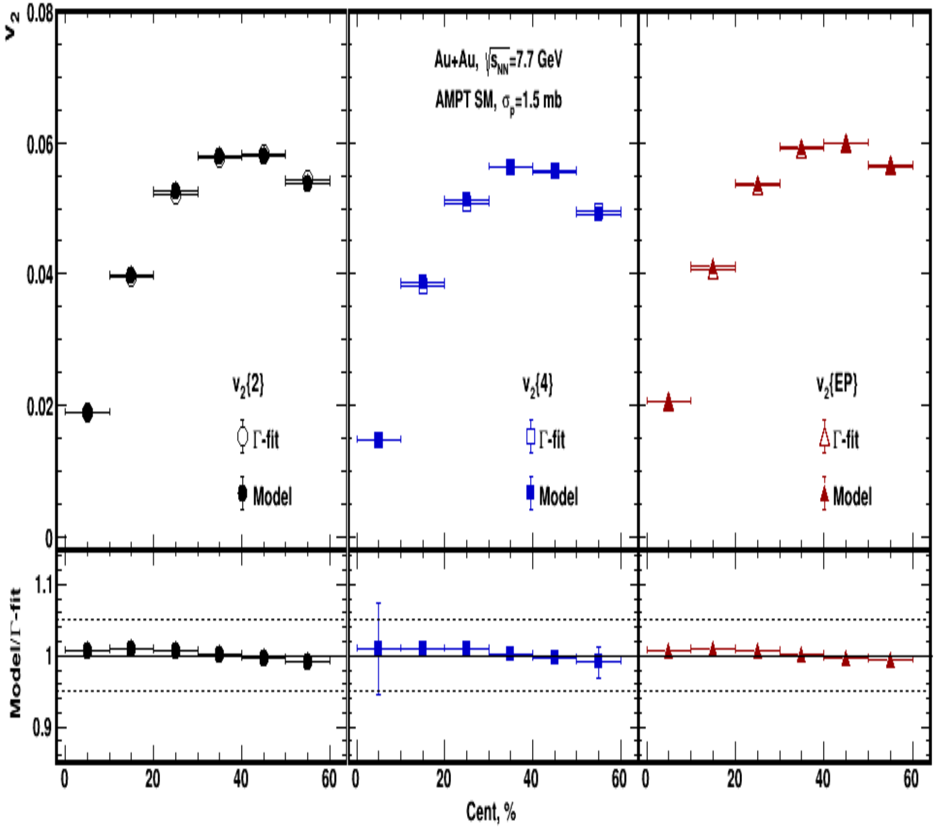
- In 10 multiplicity classes from 100 up to 1200
- PID: p, π^+, π^- , $|\eta| < 1.5$, $p_T > 200$ MeV/c
- 0.0 < b < 12.0 fm
- stat.: 1.068 B events

- $v_2\{2k\}$ are well measured in semicentral collisions
- $v_2\{2k\}$ are not well enough ordered. It could be a problem with JAM itself.
- We developed codes for calculations with and without efficiency corrections both.
- closed circles (squares): results without (with) efficiency corrections (efficiency randomly distributed between 95 and 100%)
- With real data and efficiencies the two results will differ.



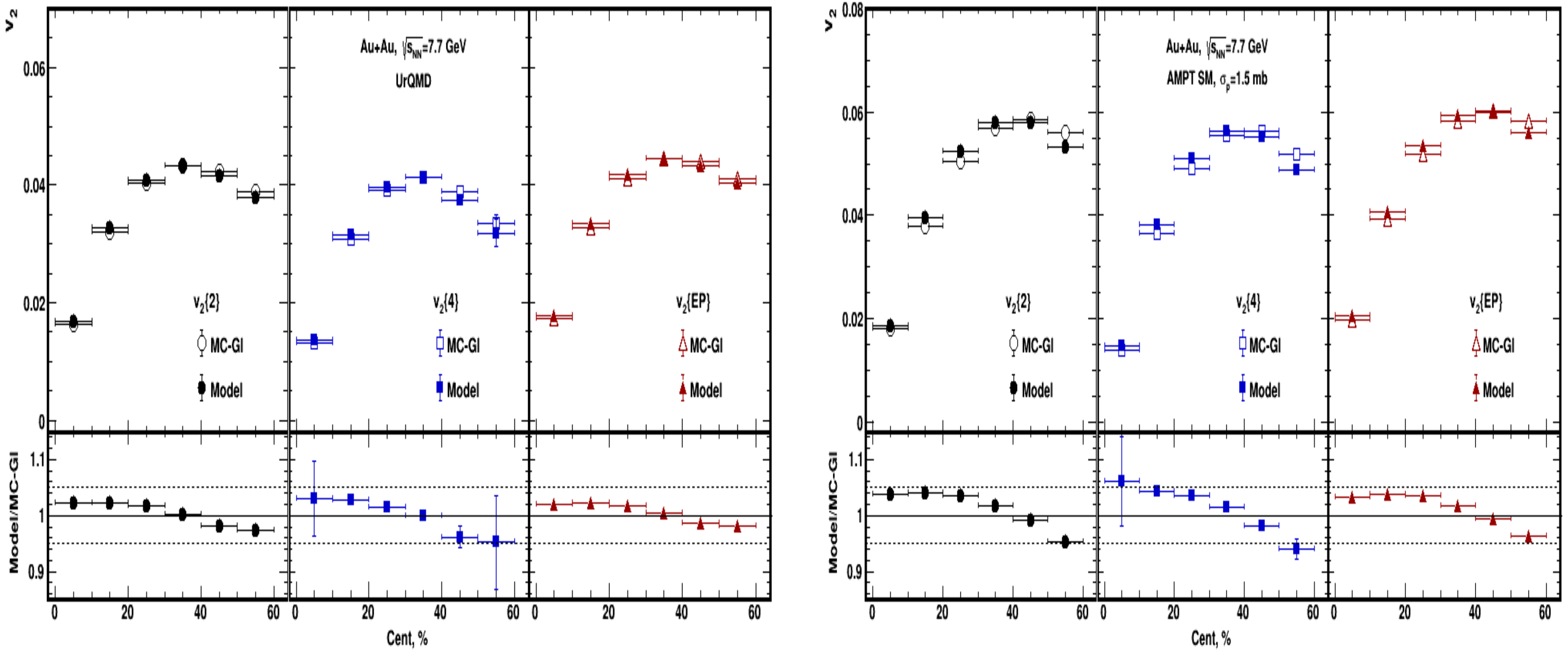
The effect of the bias in centrality determination in flow measurements for UrQMD and AMPT models (Γ-fit)





The effect of the bias caused by different centrality determination methods is within 1-2%.

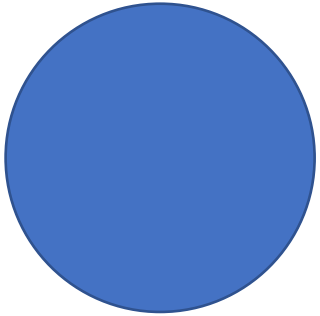
The effect of bias in centrality determination in flow measurements for UrQMD and AMPT models (MC-Glauber)



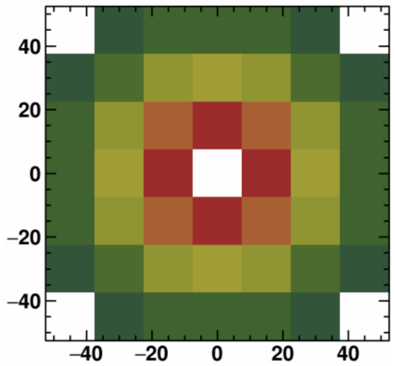
The effect of the bias caused by different centrality determination methods is within 3-5%.

Non-uniform acceptance corrections

TPC

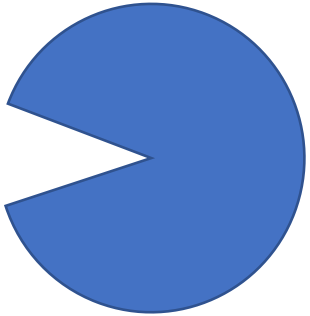


FHCal



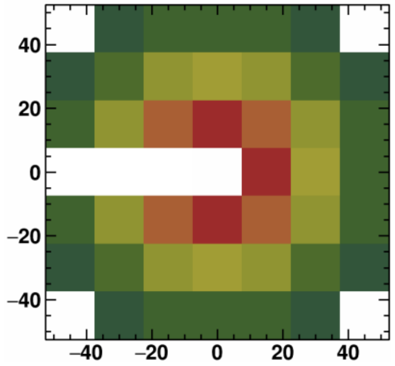
Acceptance filter

TPC



$-165° < \varphi < 165°$

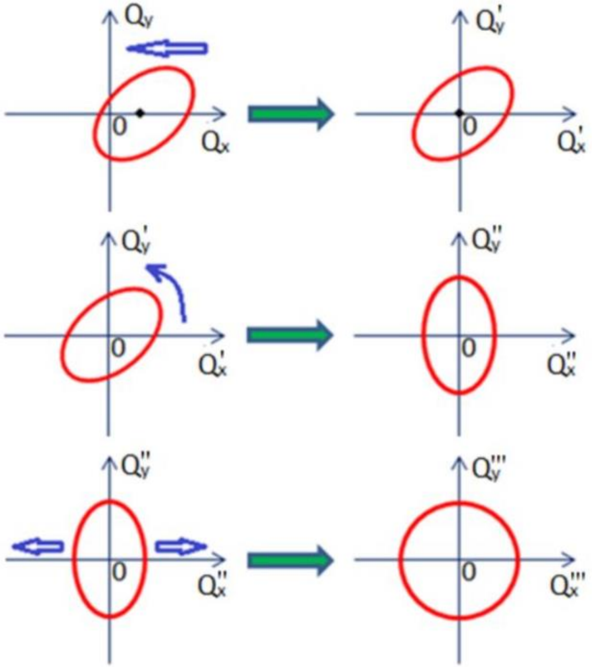
FHCal



Modules 23, 24, 25 (L) and 19, 20, 21 (R) are off

Correction for non-uniform azimuthal acceptance

1. Recentering
2. Twist
3. Rescaling



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

The QnAnalysis package

P. Parfenov MPD Cross-PWG Meeting 12/04/2022

Motivation:

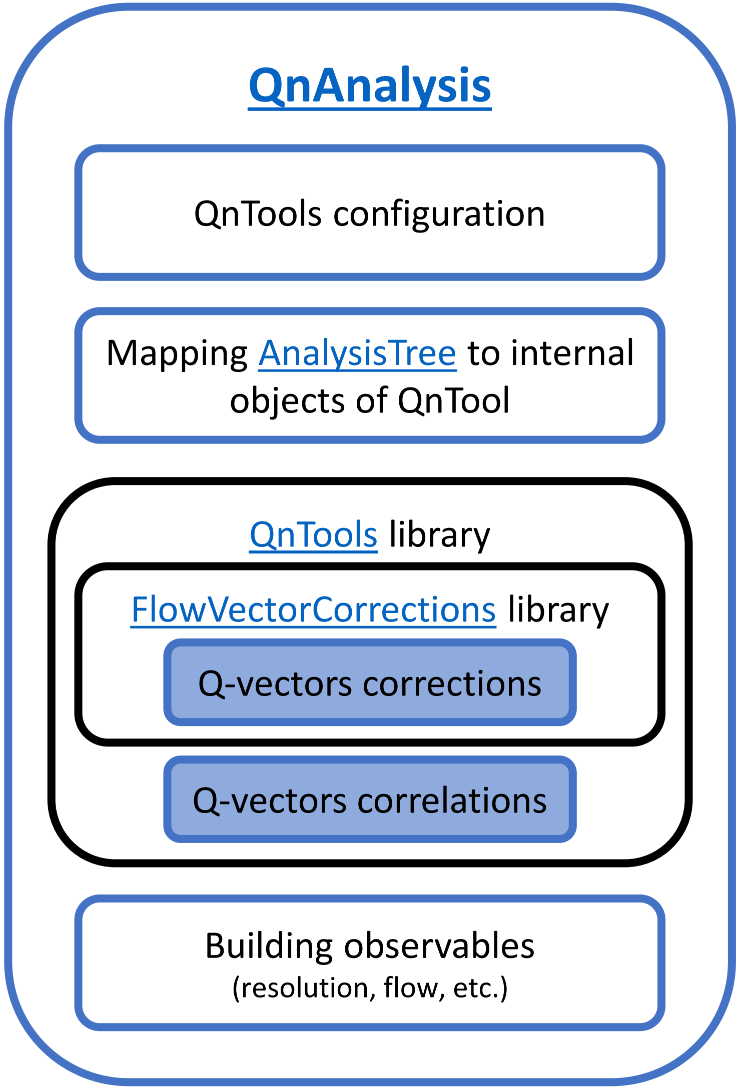
- Decoupling configuration from implementation
- Persistency of analysis setup
- Co-existence of different setups (easy systematics study)
- Unification of analysis methods
- Self-descriptiveness of the analysis results

QnAnalysis requirements:

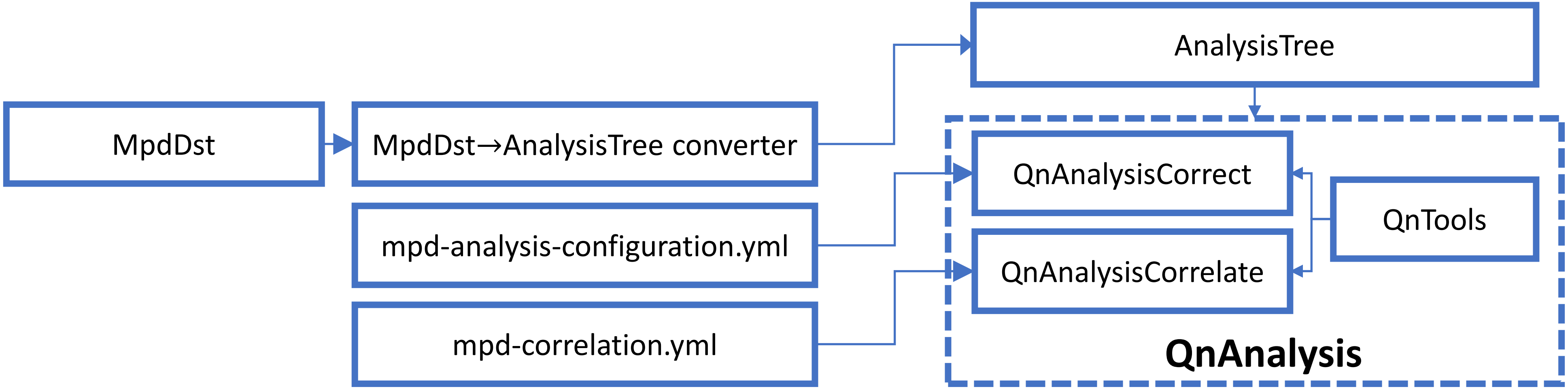
- ROOT ver. ≧ 6.20 (with MathMore library)
- C++17 compatible compiler
- CMake ver. ≧ 3.13

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

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



QnAnalysis implementation in MPD experiment



MPD-specific interface:

- **MpdDst→AnalysisTree converter:** converter from MpdDst to AnalysisTree format
- YAML configuration files for QnAnalysis:
  - **mpd-analysis-configuration.yml**: sets up Q_n, u_n vectors to collect (cuts, correction steps, …)
  - **mpd-correlation.yml:** sets up correlations between previously collected Q_n, u_n vectors

General interface:

- **AnalysisTree:** A framework-independent, lightweight and flexible data format
- **QnTools:** set of tools for multidimentional Q-vector-based corrections and correlations:
  - **QnAnalysisCorrect**: collects Q_n, u_n vectors
  - **QnAnalysisCorrelate**: make correction between collected Q_n, u_n vectors

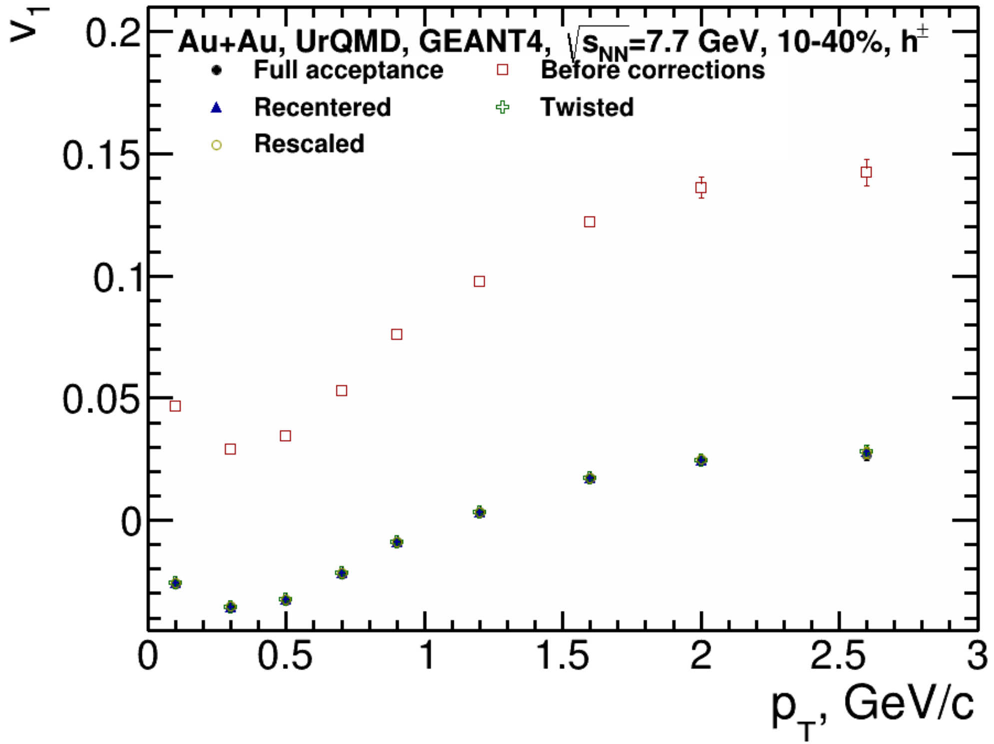
Joint development with FAIR (CBM for NICA)

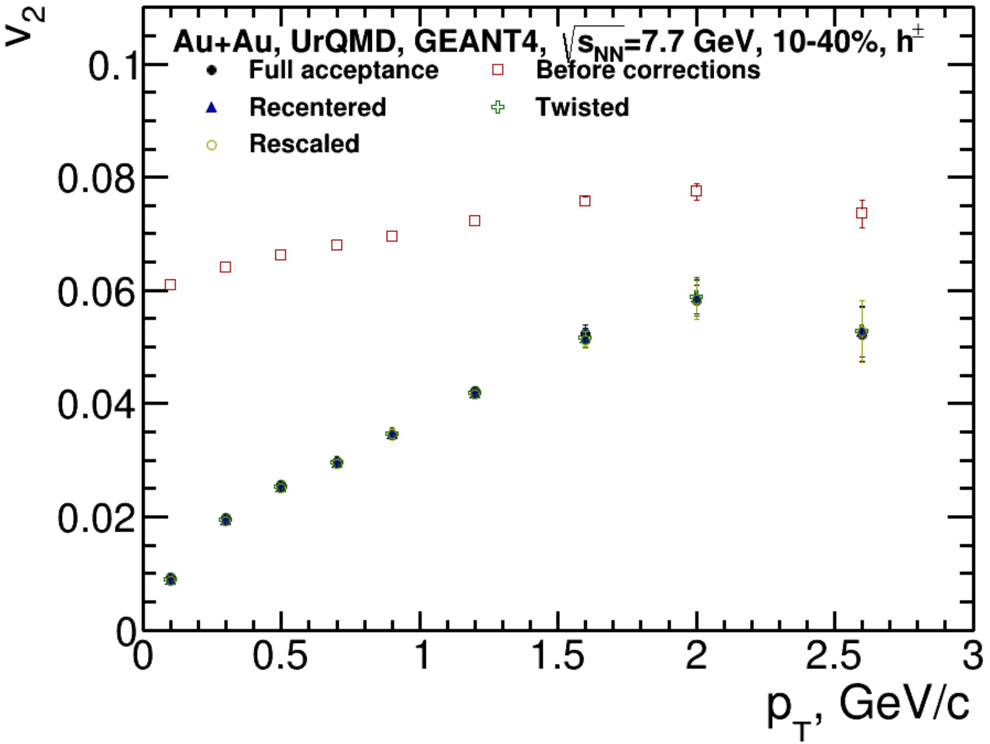
QnAnalysis is already used in the current (HADES, ALICE) and future (CBM) experiments – now available for MPD

QnAnalysis git link: https://github.com/HeavyIonAnalysis/QnAnalysis

AnalysisTree git link: https://github.com/HeavyIonAnalysis/AnalysisTree

Effects of non-uniformity corrections

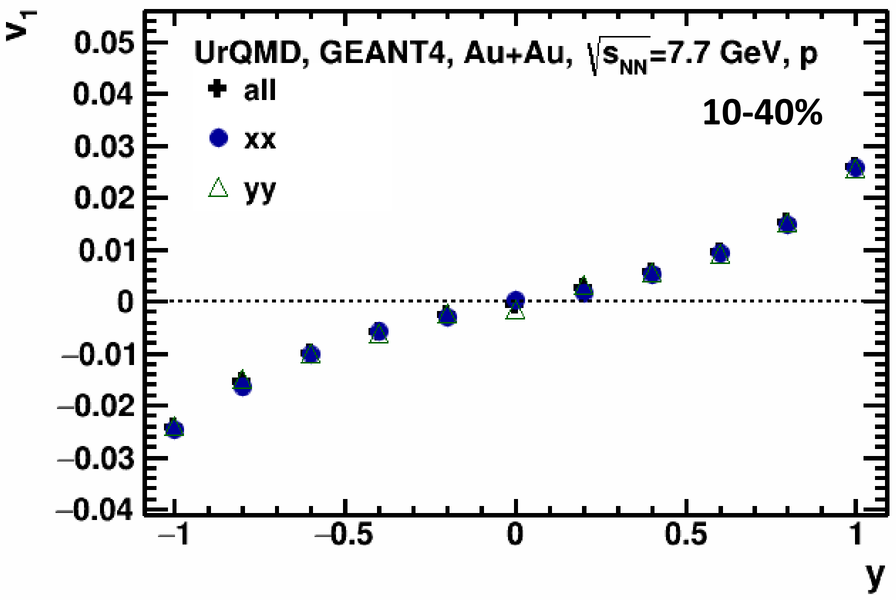


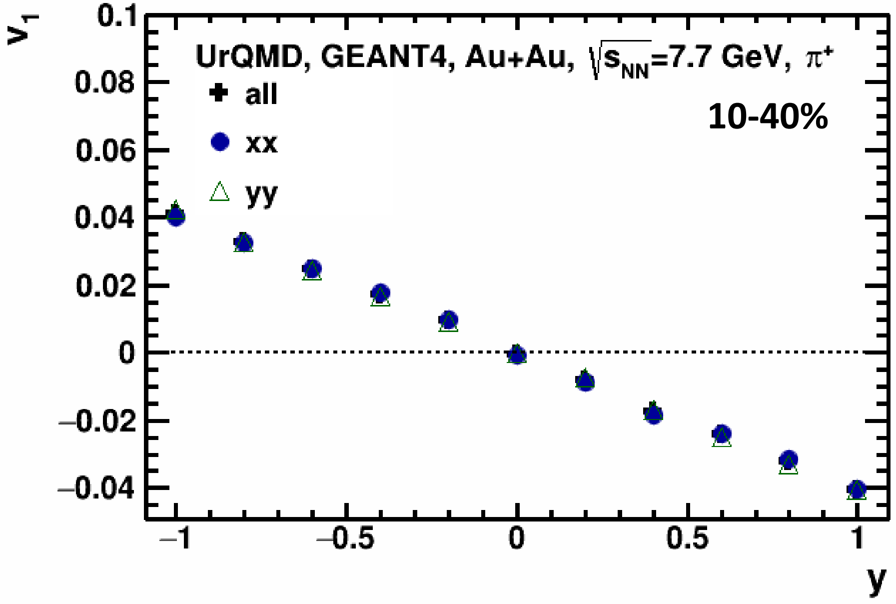


Q-vector	Q_n weight	Correction axes	Correction steps	Error calculation	Q_n normalization
Spectators (FHCal)	Module energy	b [0,12], 8 bins	Recentering Twist Rescaling	Bootstrapping, 50 samples	Sum of weights
Charged hadrons (TPC)	1	pT [0,3], 9 bins b [0,12], 8 bins			

Good agreement between v_n with acceptance non-uniformity corrections and full acceptance

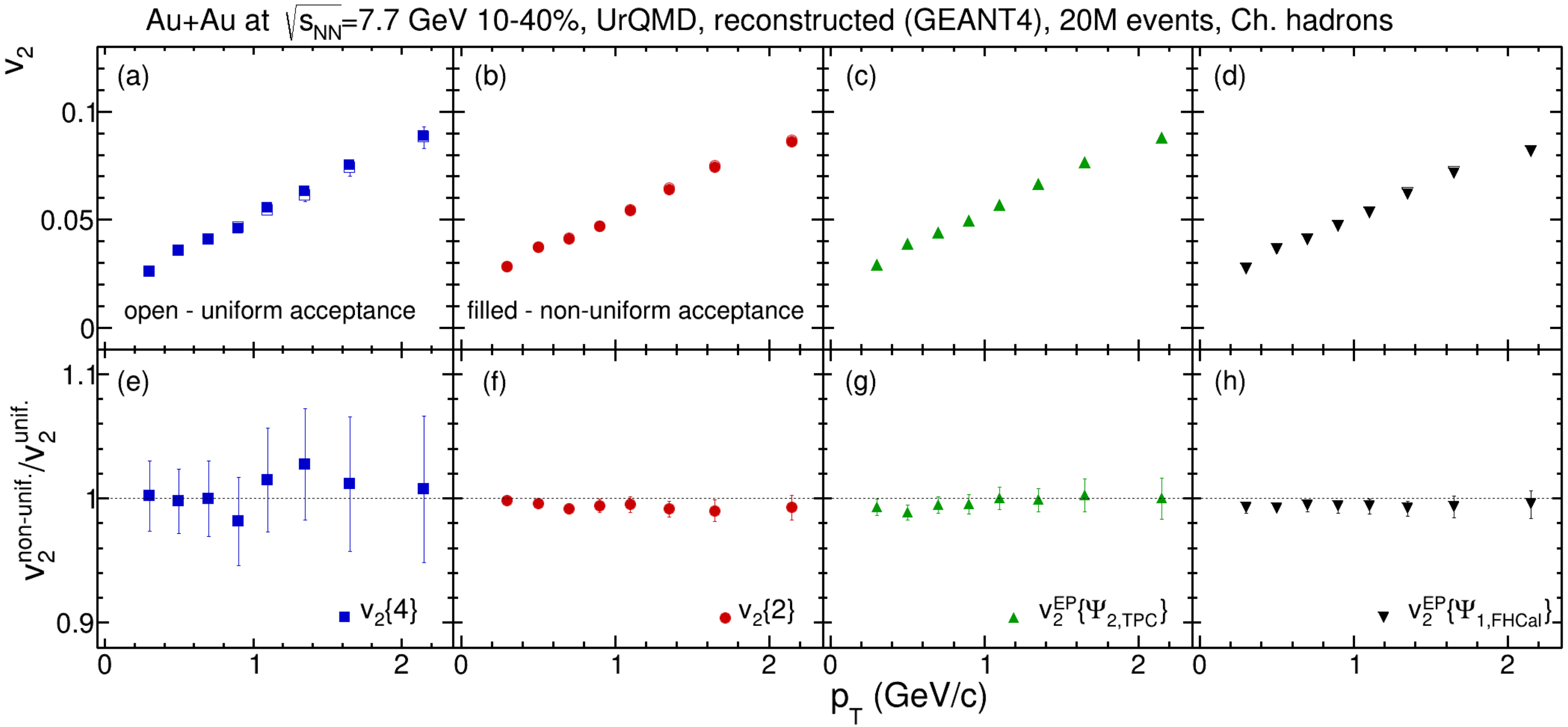
Components comparison: v_1





$v_{1,XX}$, $v_{1,YY}$ and $v_{1,all}$ are consistent with each other

Acceptance correction



The applied acceptance corrections eliminated the influence of non-uniform acceptance

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

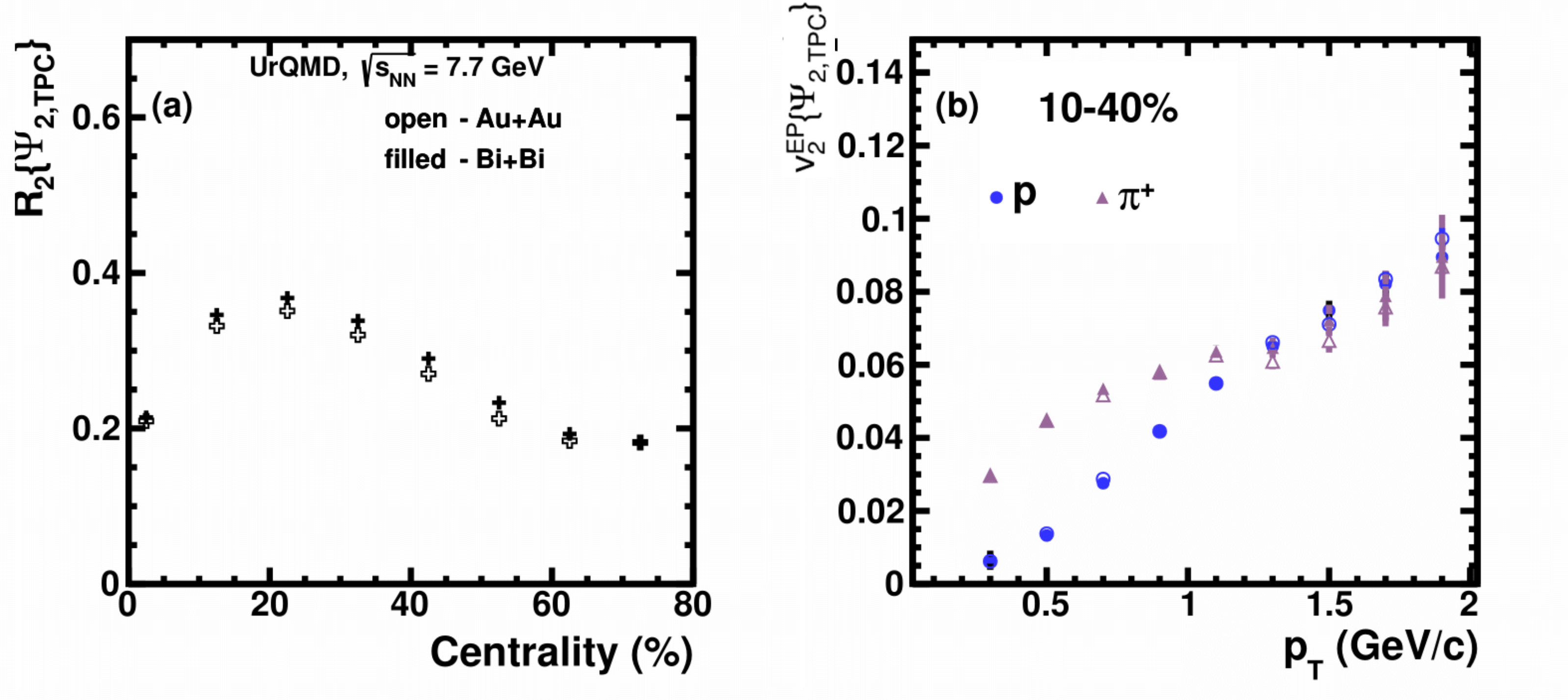
Results for 2019-2022

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

23 presentations at conferences and workshops, 17 publications and 3 master diploma works

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

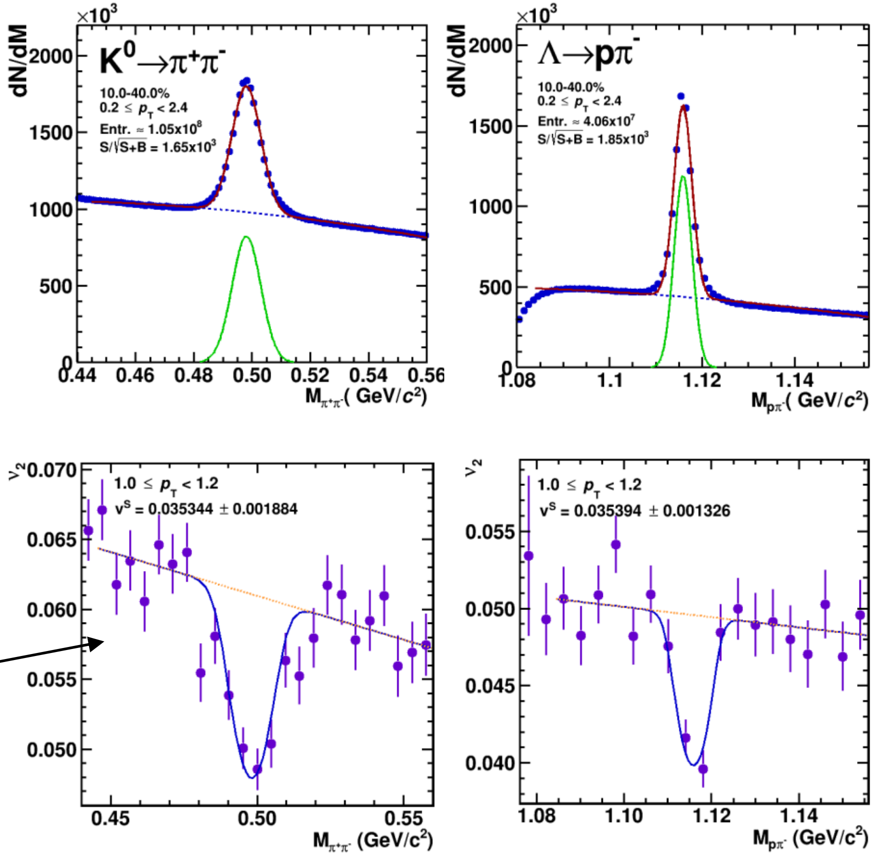
Geant4 simulation, full reconstruction with:

- 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

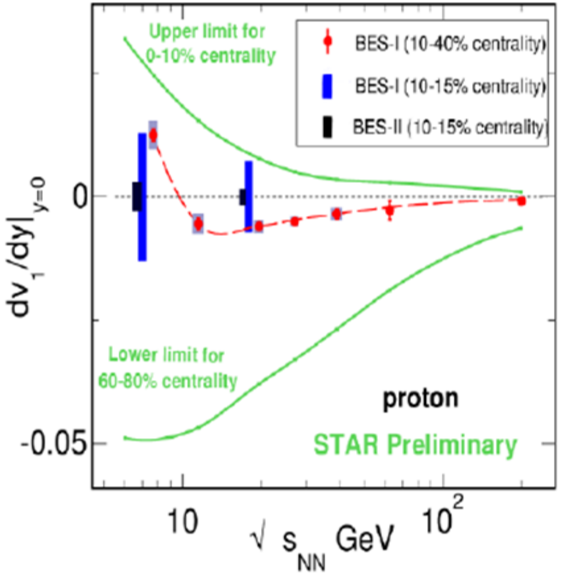
$$v_2^{SB}(m_{inv},p_T) = v_2^{S}(p_T)\frac{N^{S}(m_{inv},p_T)}{N^{SB}(m_{inv},p_T)} + v_2^{B}(m_{inv},p_T)\frac{N^{B}(m_{inv},p_T)}{N^{SB}(m_{inv},p_T)}$$



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

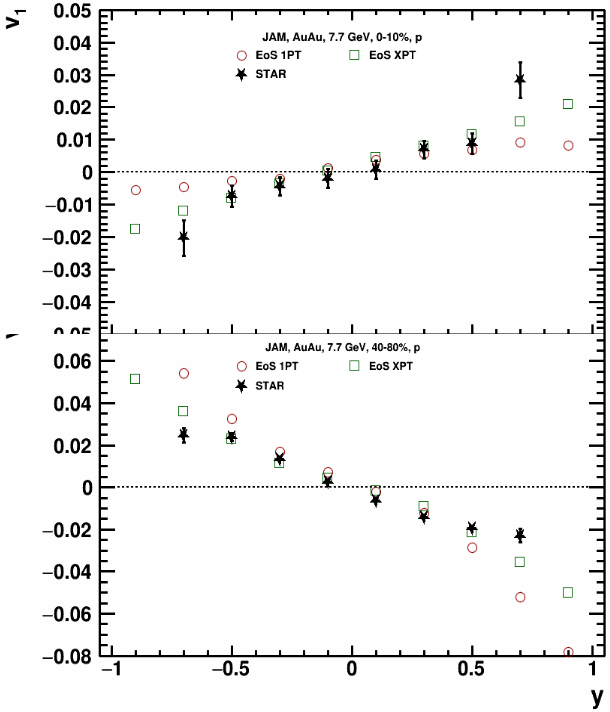
- Multi-variate analysis for reconstructed particle selection (TMVA)
- KFParticle

v_1 study at NICA energies



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

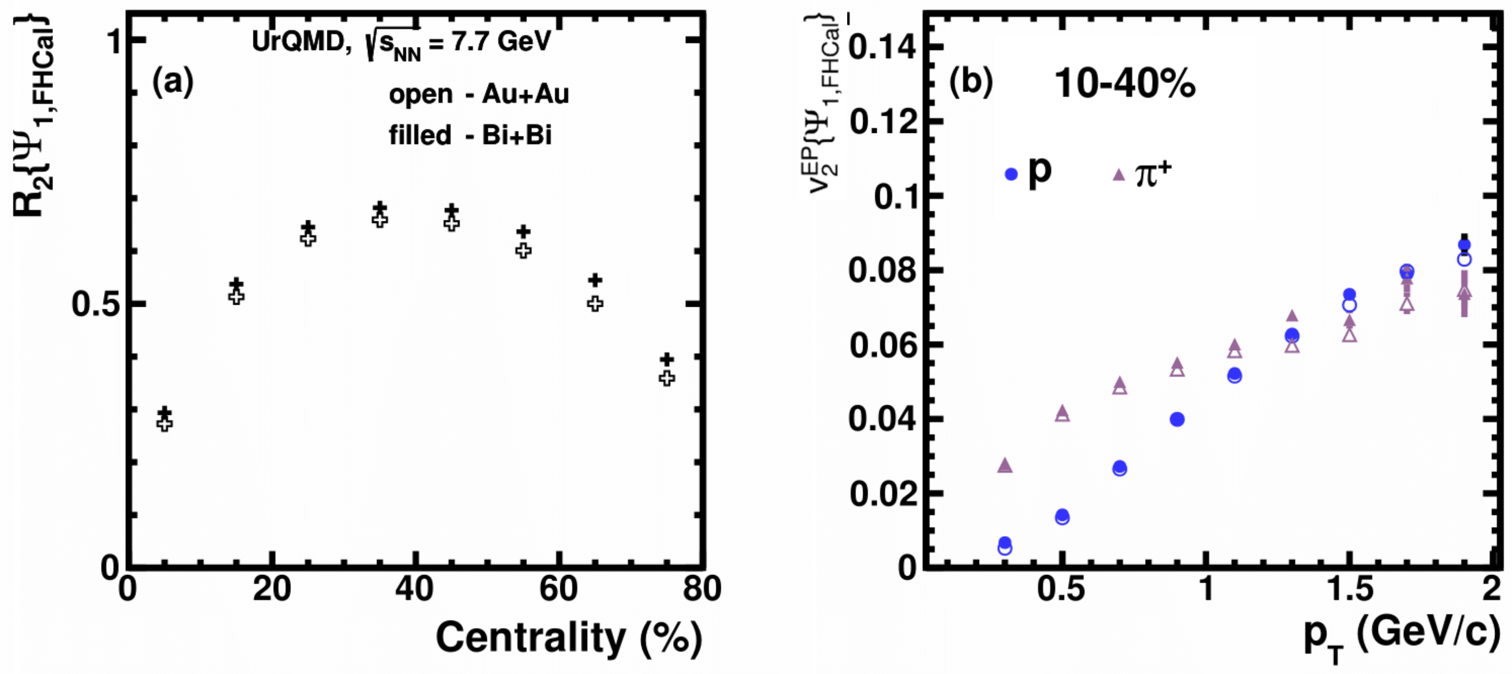
P. Parfenov, The Conference "RFBR Grants for NICA", Dubna (2020)



dv_1/dy slope changes dramatically with centrality for protons

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

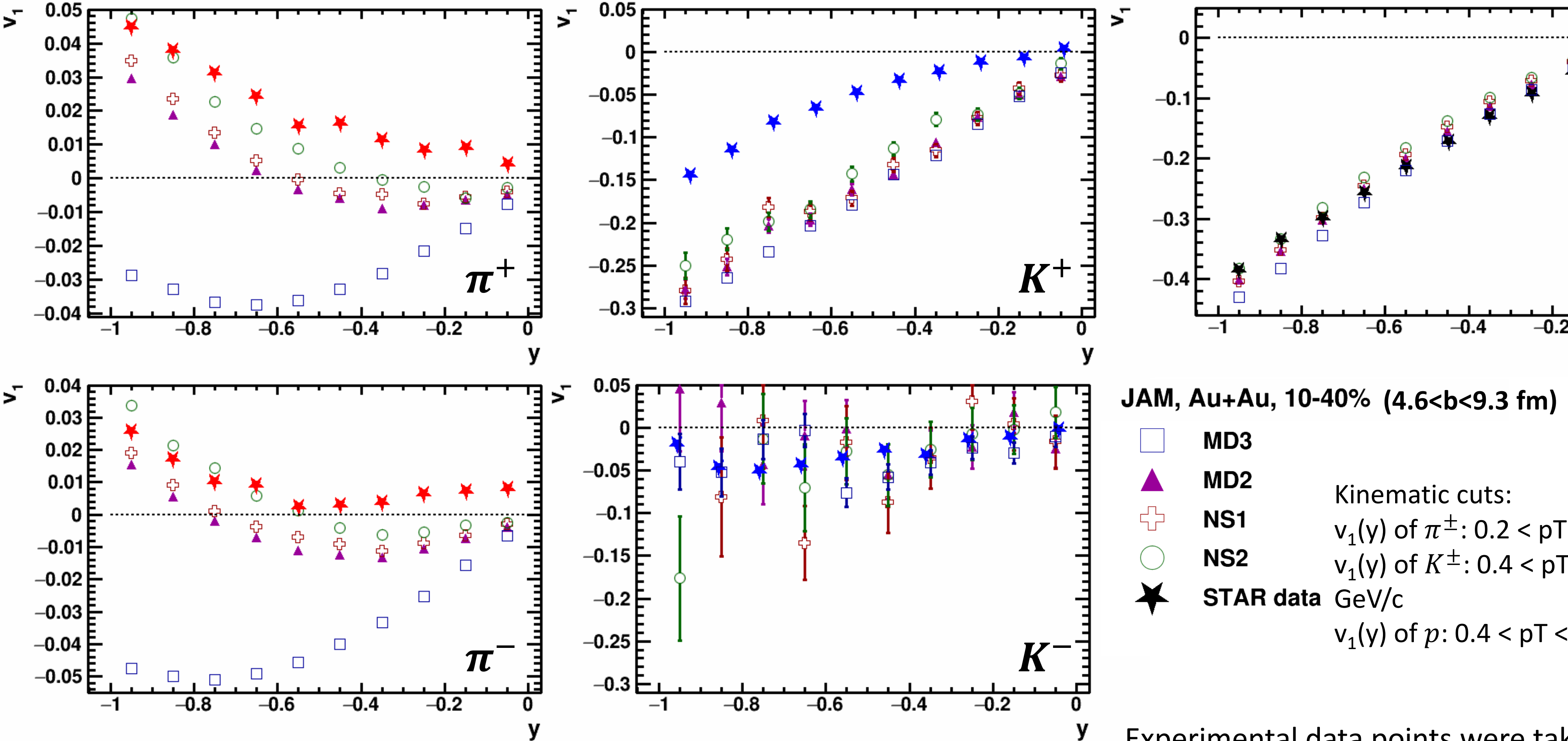
- FHCal event plane



- 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

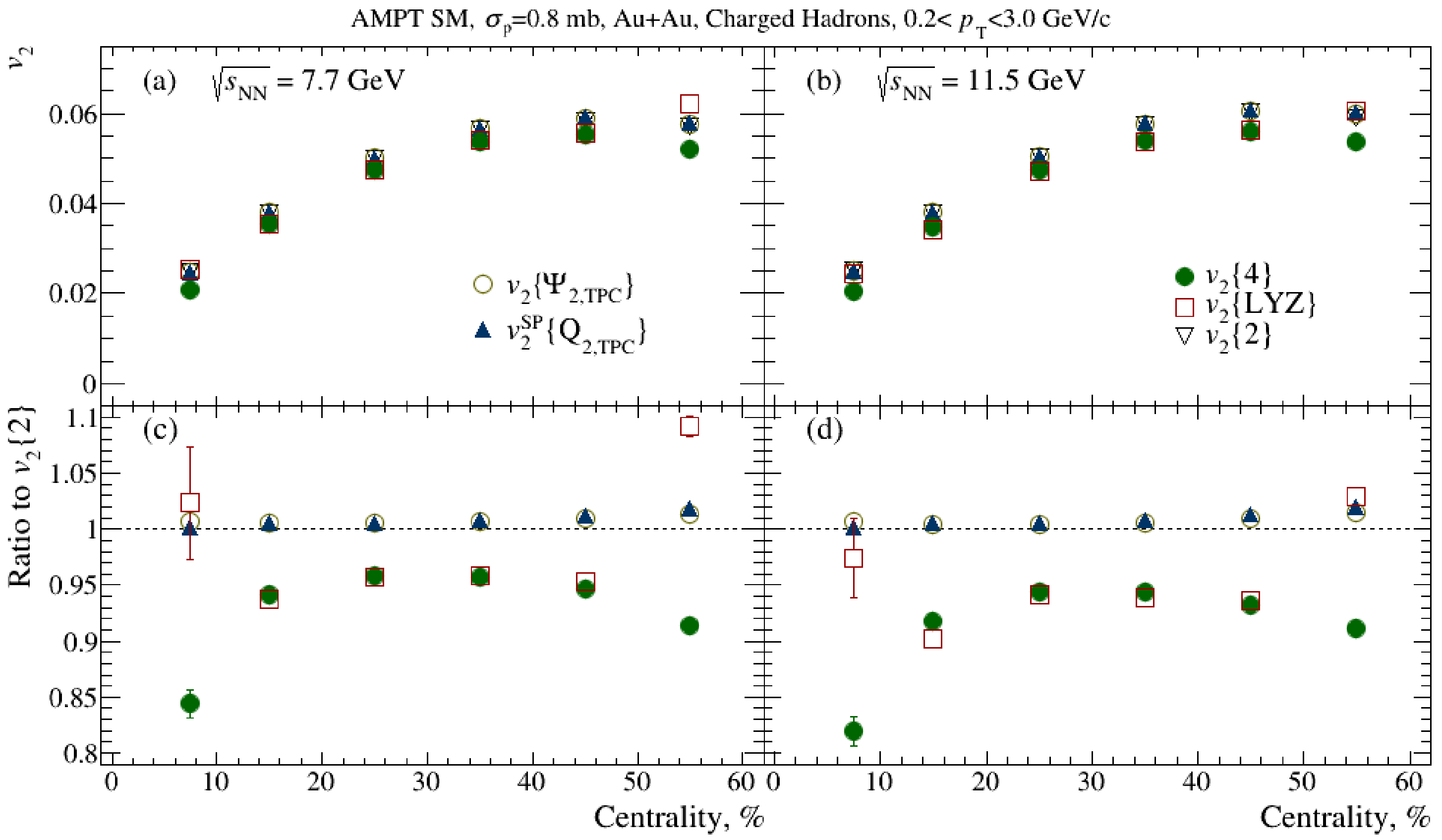


Kinematic cuts:
$v_1(y)$ of $\pi^{\pm}$: 0.2 < pT < 1.6 GeV/c
$v_1(y)$ of $K^{\pm}$: 0.4 < pT < 1.6 GeV/c
$v_1(y)$ of p: 0.4 < pT < 2.0 GeV/c

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

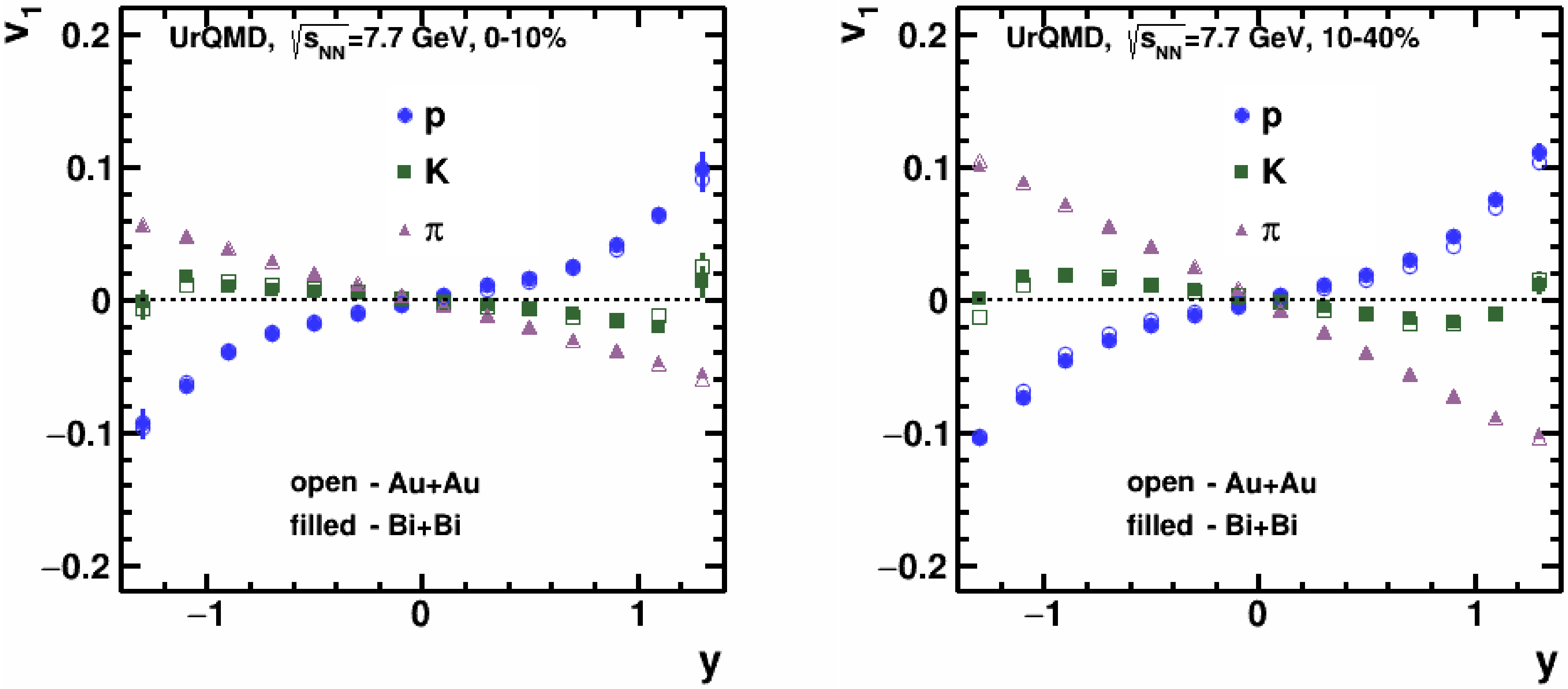
Experimental data points were taken from:
Mohamed Abdallah et al. [STAR Collaboration] 2108.00908 [nucl-ex]

Centrality dependence of v_2\{methods\}



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

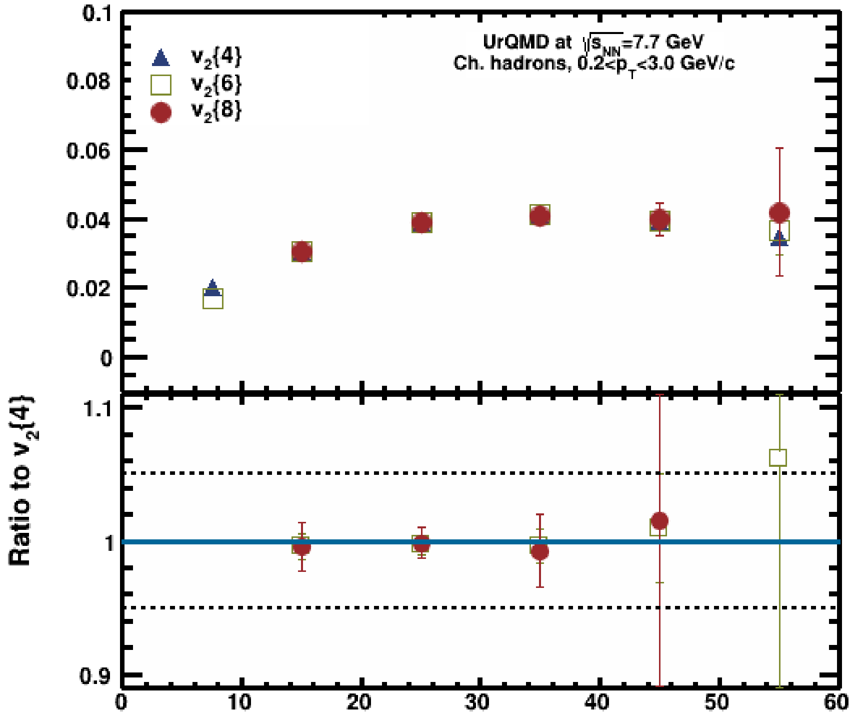
$v_1(y)$: Bi+Bi vs Au+Au



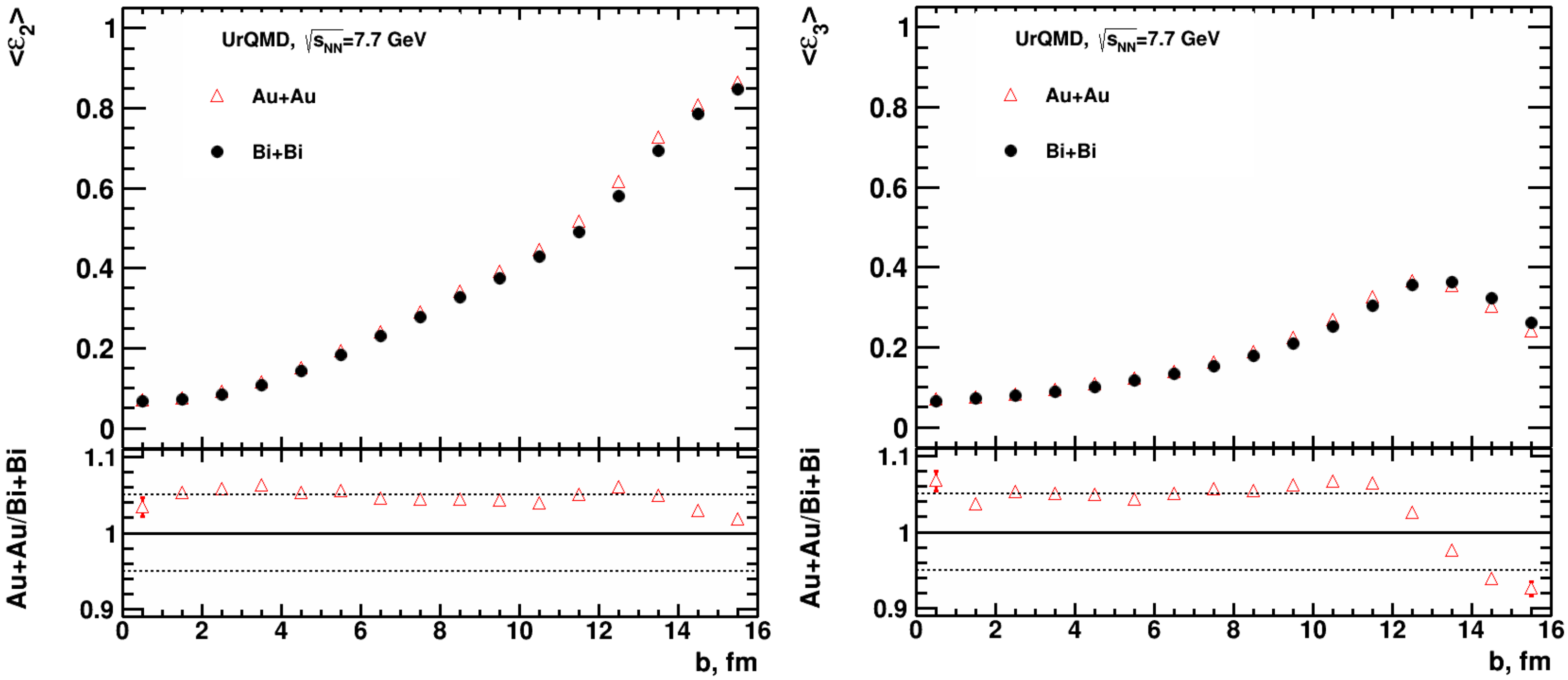
Expected small difference for v1 (y) for particles produced in Au+Au and Bi+Bi collisions.

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