PWG3 Summary:
Anisotropic collective flow and development of the corresponding measurement techniques for the MPD experiment

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

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For the MPD Collaboration

XI MPD Collaboration Meeting, JINR, Dubna, 18-20 April 2023

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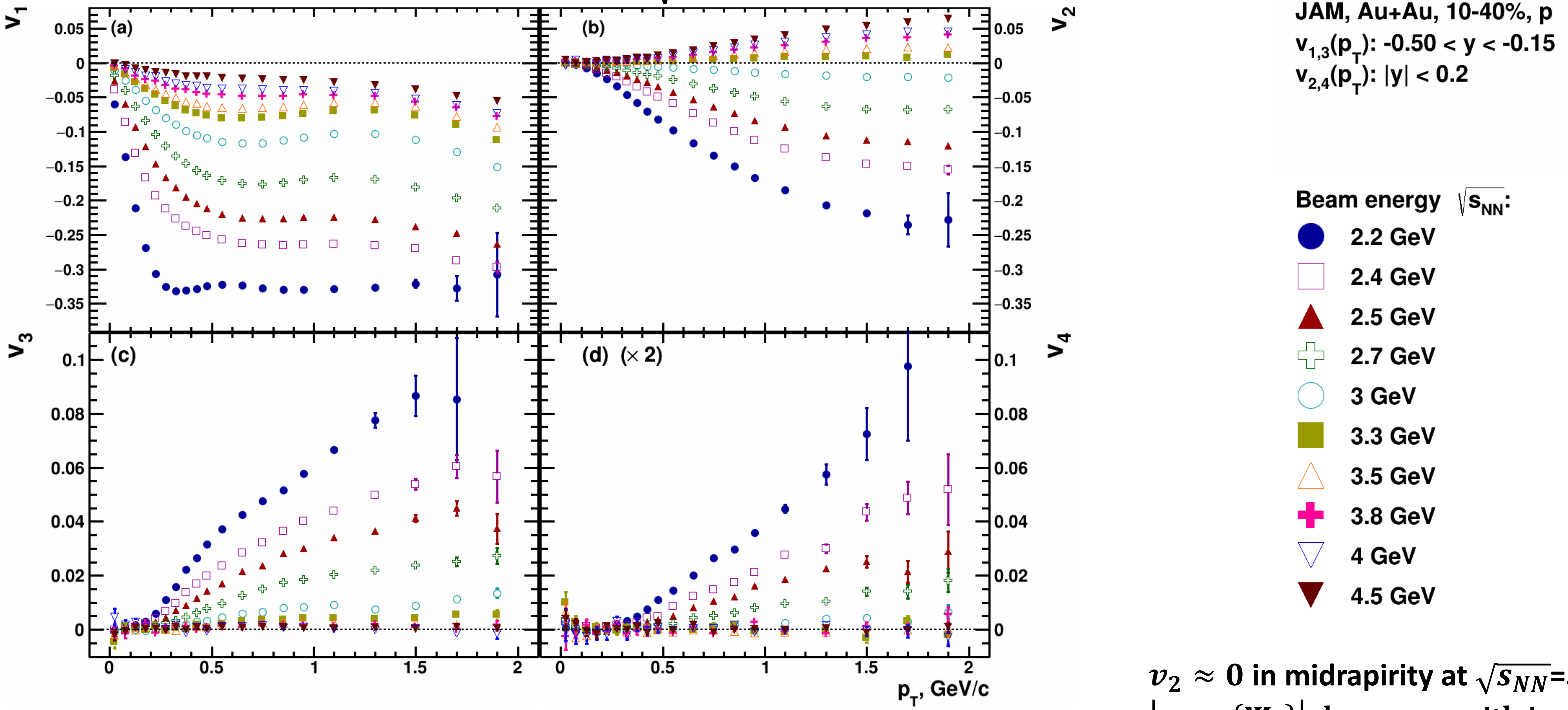
Model study of v_n at $\sqrt{s_{NN}}$=2.4-4.5 GeV



$v_2 \approx 0$ in midrapirity at $\sqrt{s_{NN}}$=3.3 GeV

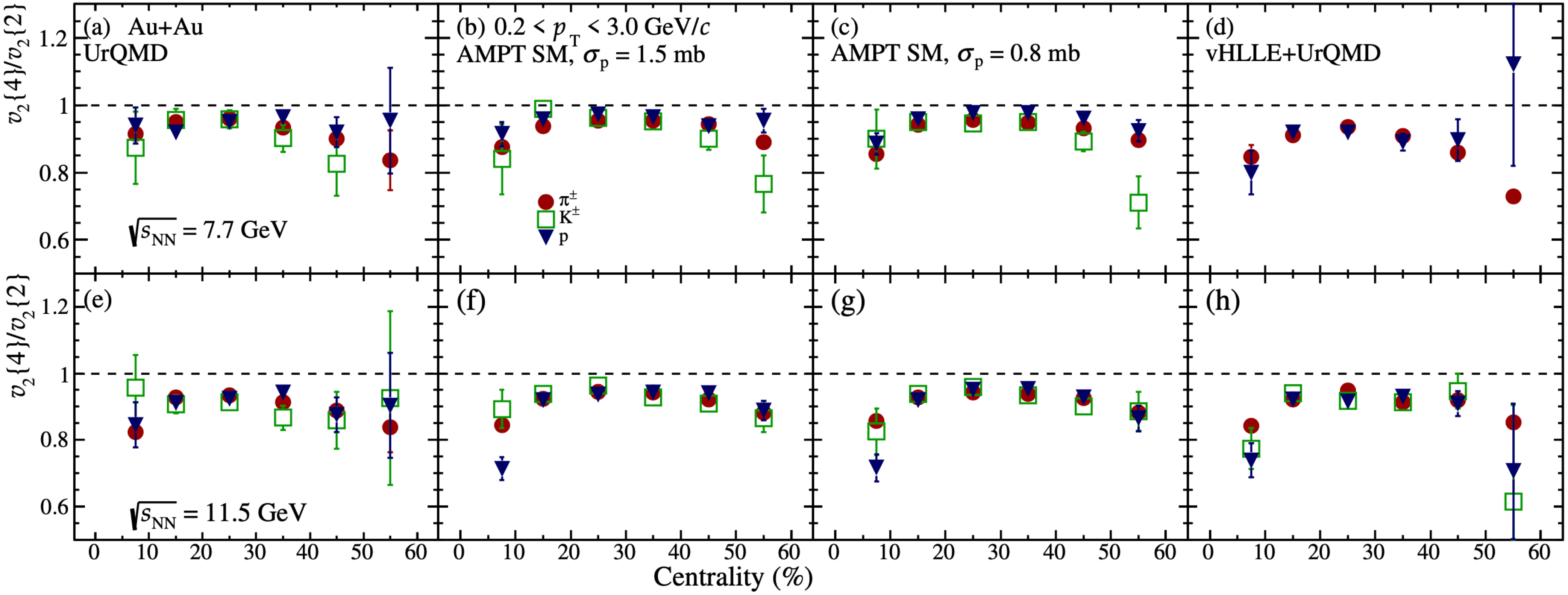
$|v_{1,3,4}\{\Psi_1\}|$ decreases with increasing collision energy

$v_{3,4} \approx 0$ at $\sqrt{s_{NN}} \geq 3.3$ GeV

Detailed study of v_n was done for Nuclotron-NICA energies

More details are in **P. Parfenov, Particles 5 (2022) 4, 561-579**

Elliptic flow and its fluctuations at $\sqrt{s_{NN}}$=7.7, 11.5 GeV

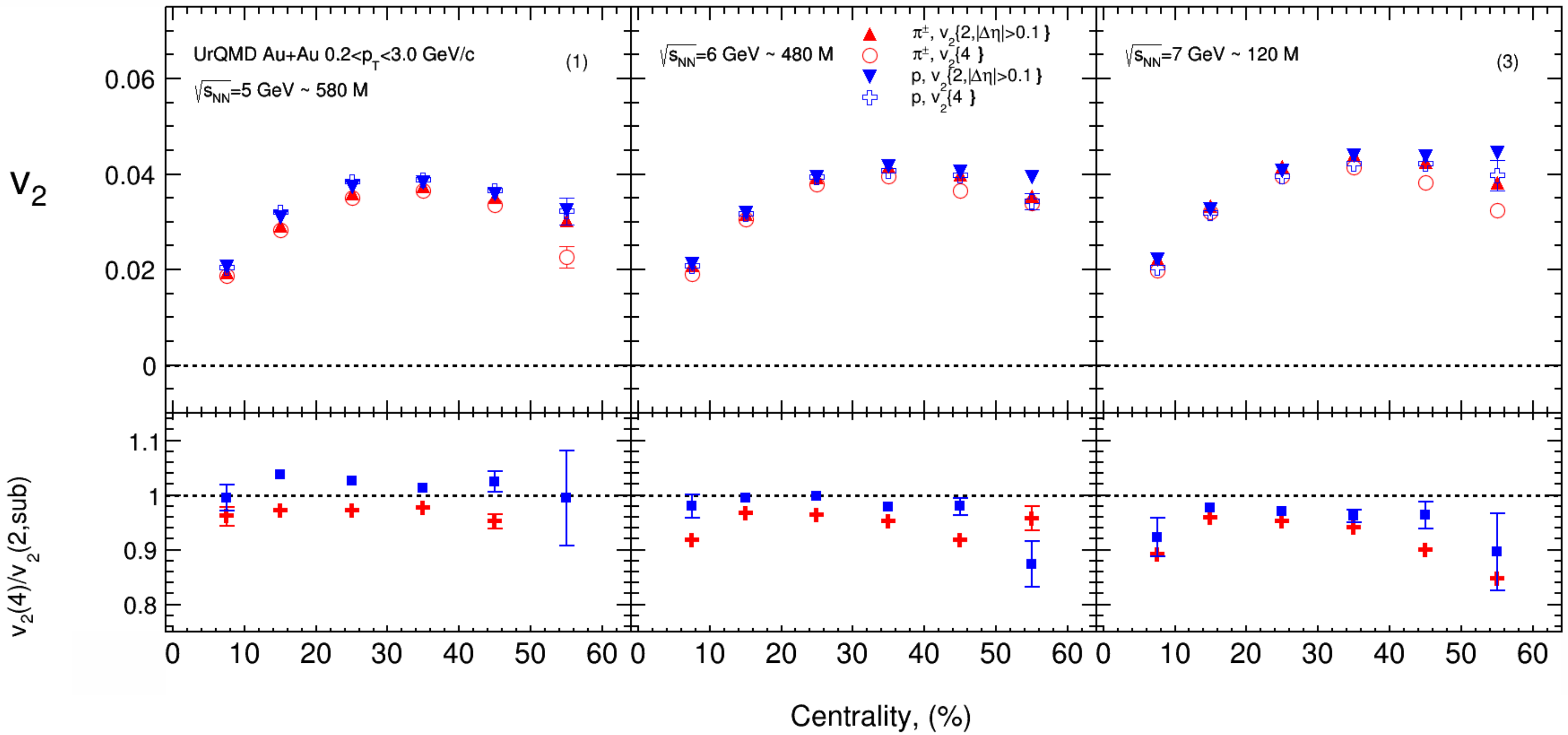


v_2 fluctuations originate from participant eccentricity fluctuations

Weak dependence on particle species is observed for $\sqrt{s_{NN}}$=7.7, 11.5 GeV

More details are in **V.B. Luong, D. Idrisov, P. Parfenov, A. Taranenko, Particles 6 (2022) 1, 17-29**

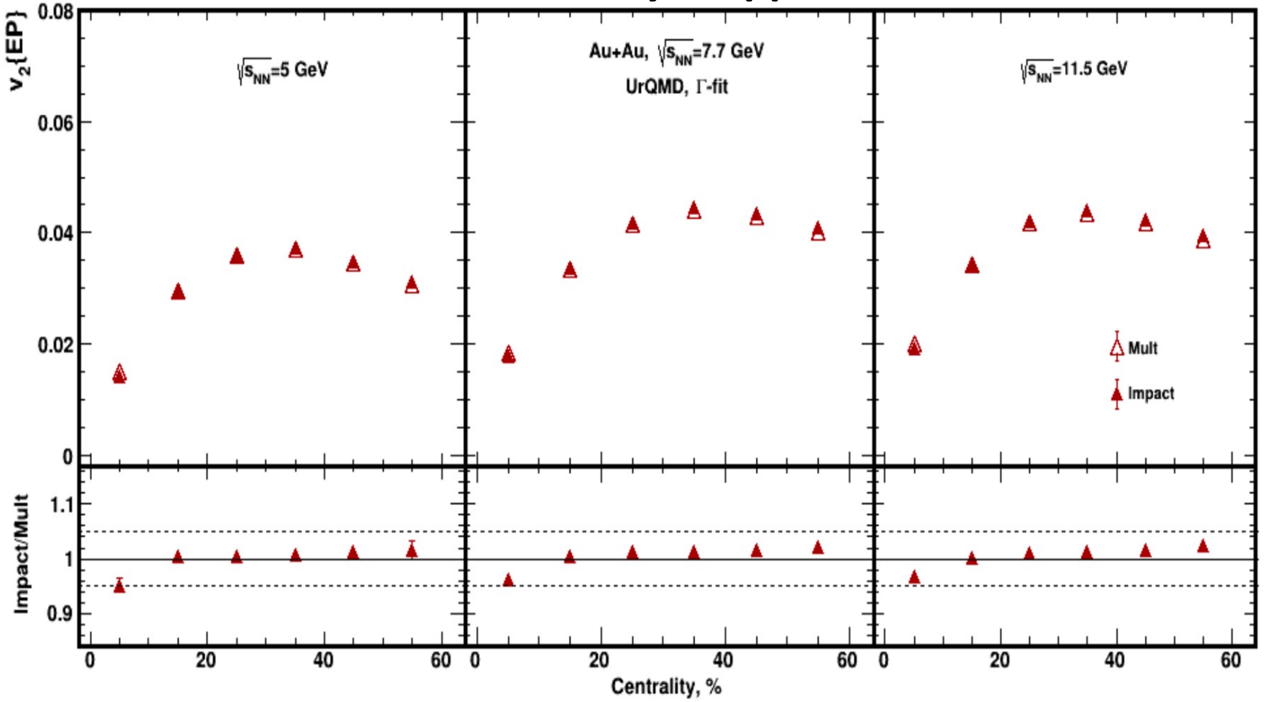
Relative v_2 fluctuations of pions and protons



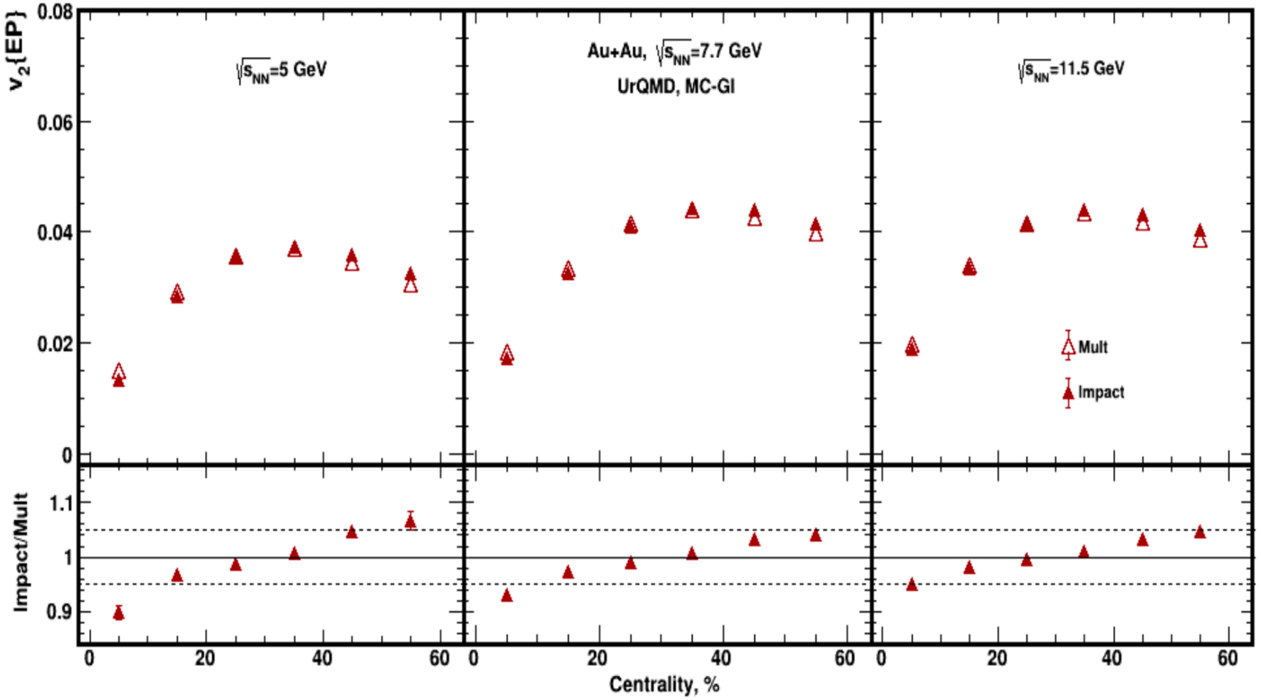
- $v_2\{4\}\ /v_2\{2\}$ differs for pions and protons at $\sqrt{s_{NN}} < 6$ GeV
- $v_2\{4\}\ /v_2\{2\} < 1$ at $\sqrt{s_{NN}} > 5$ GeV for pions and at $\sqrt{s_{NN}} > 6$ GeV for protons
- More statistics needed to make comparison of $v_2\{4\}\ /v_2\{2\}$ protons and antiprotons

Centrality selection effect on v_2

Inverse bayes approach



MC-Glauber approach

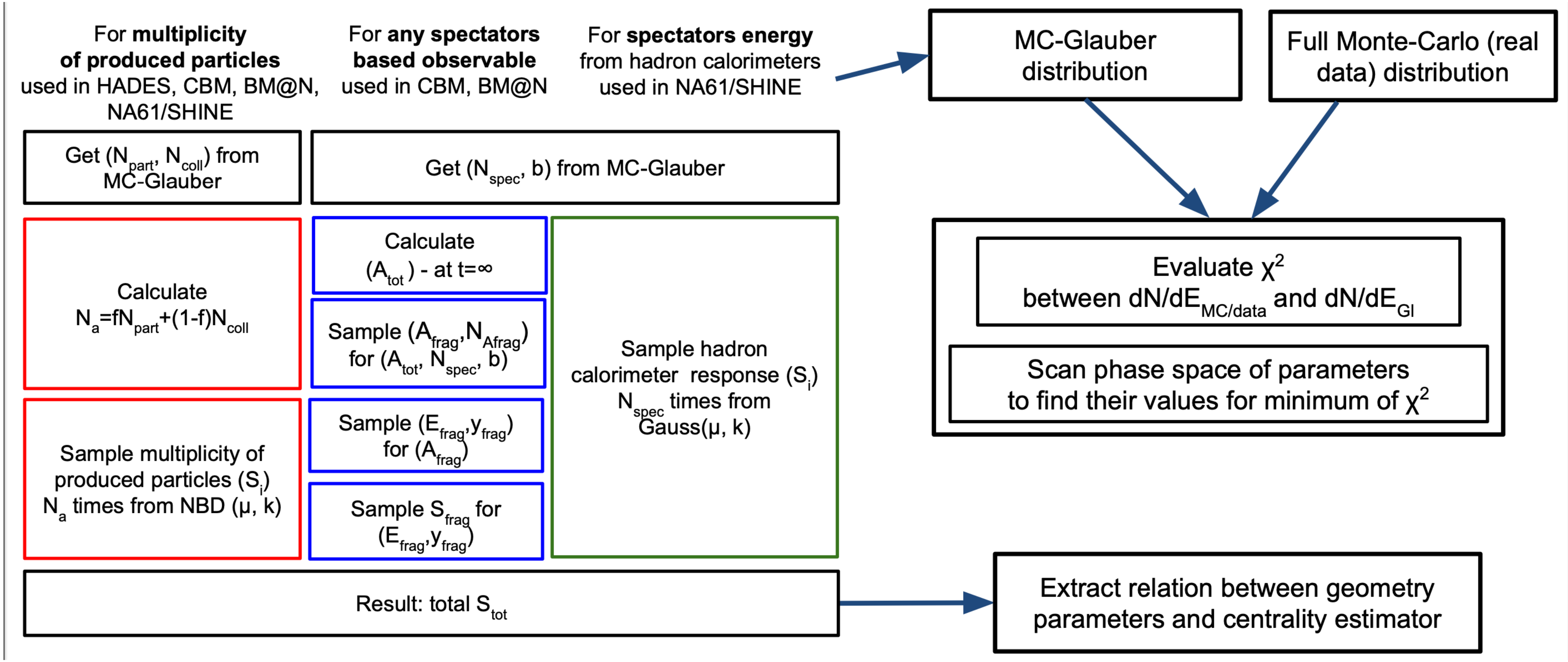


Difference in v_2 from centrality selection decreases with $\sqrt{s_{NN}}$

Similar trends are observed for all methods of v_2 measurement

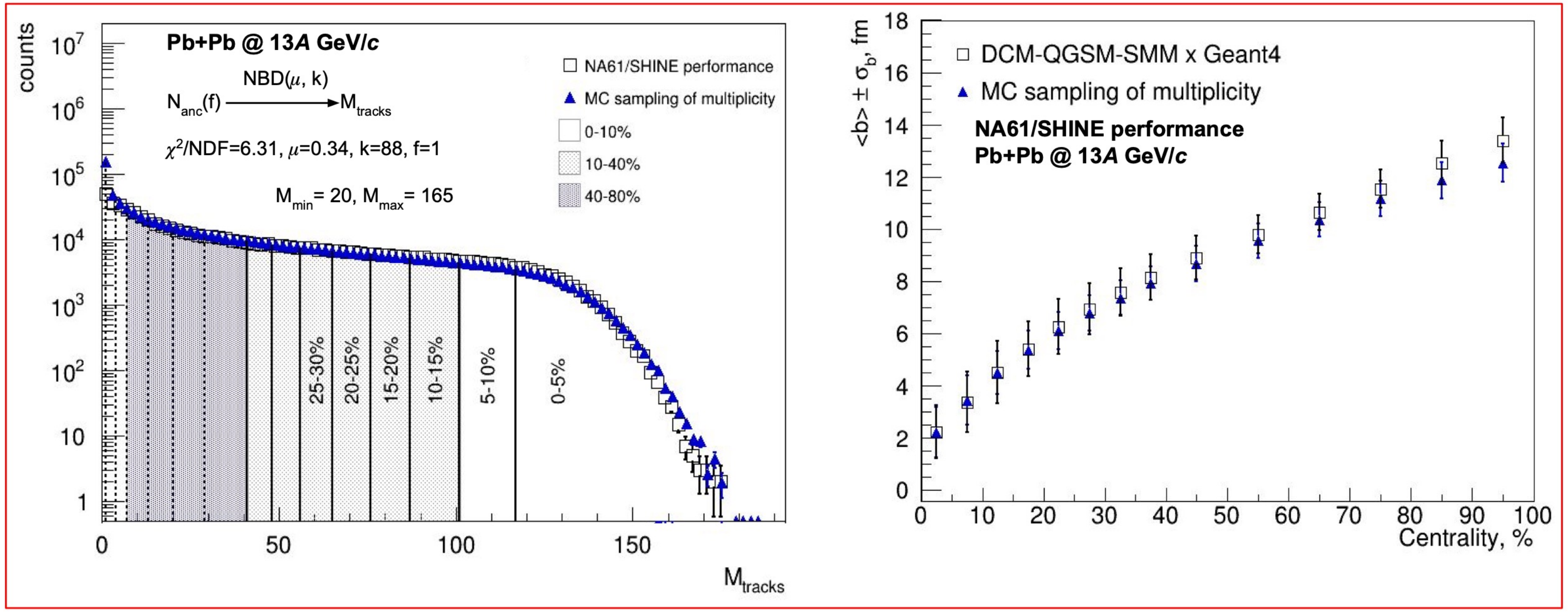
Paper is accepted for publication in **D. Idrisov, P. Parfenov, A. Taraneko, Particles** journal

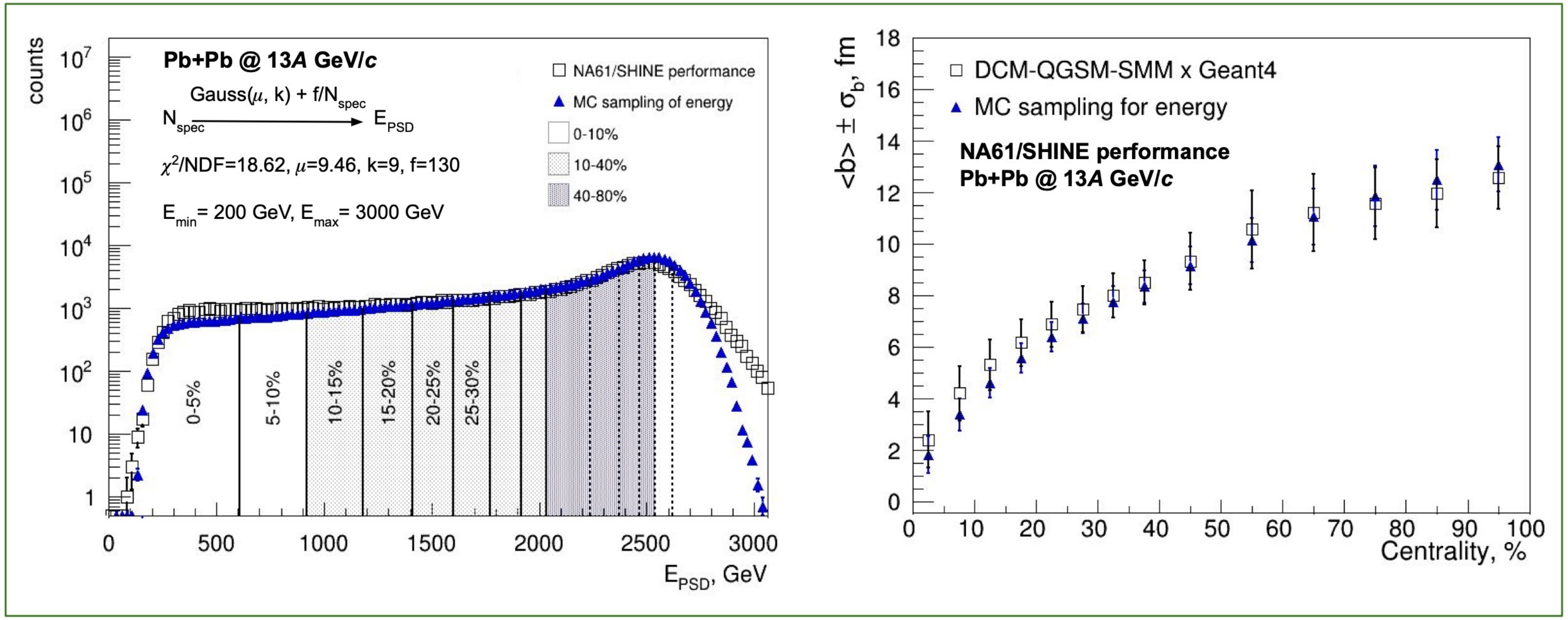
Centrality determination in MPD using MC Glauber



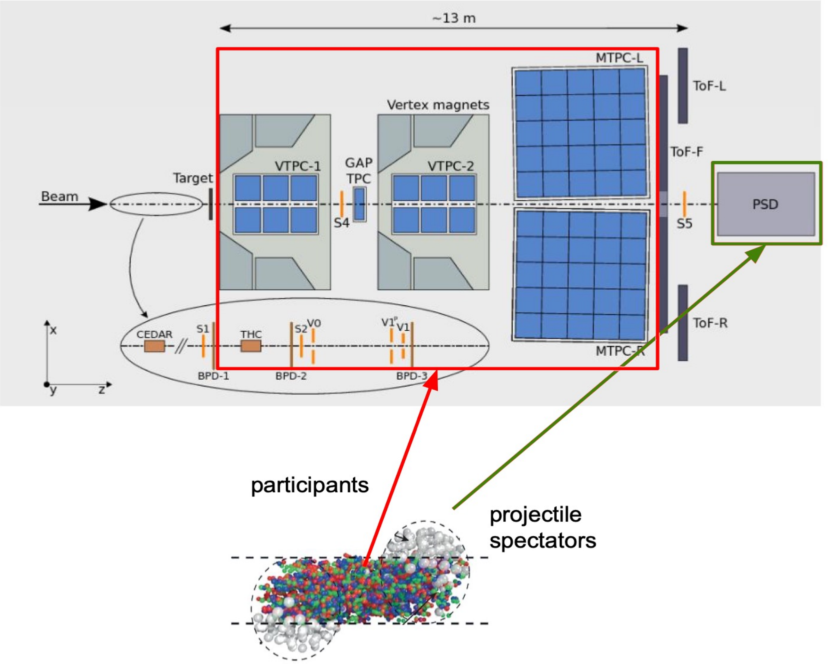
Centrality can be estimated based on multiplicity of produced charged particles or spectator energy – **see more details in I.Segal's talk on Cross-PWG 14.02.2023**

Centrality determination in MPD using MC Glauber





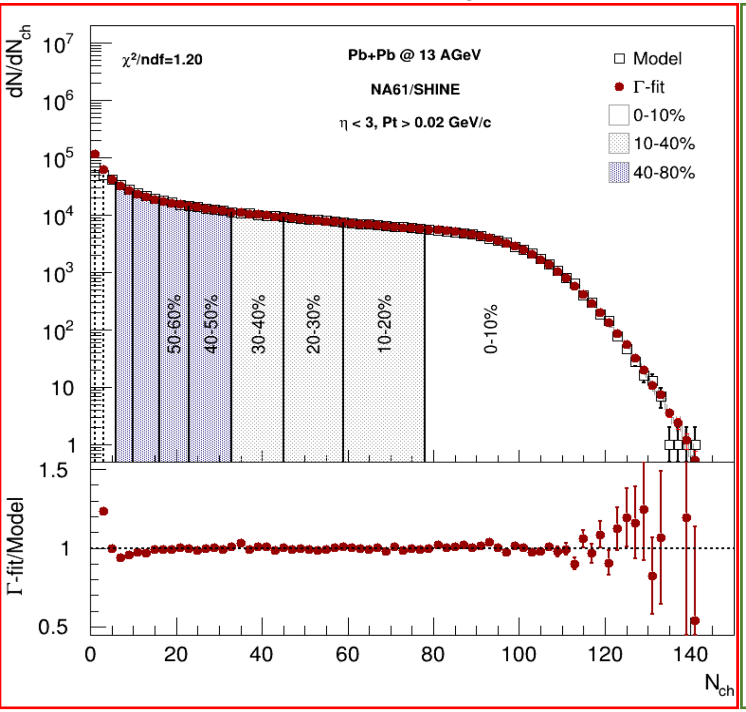
NA61/SHINE setup

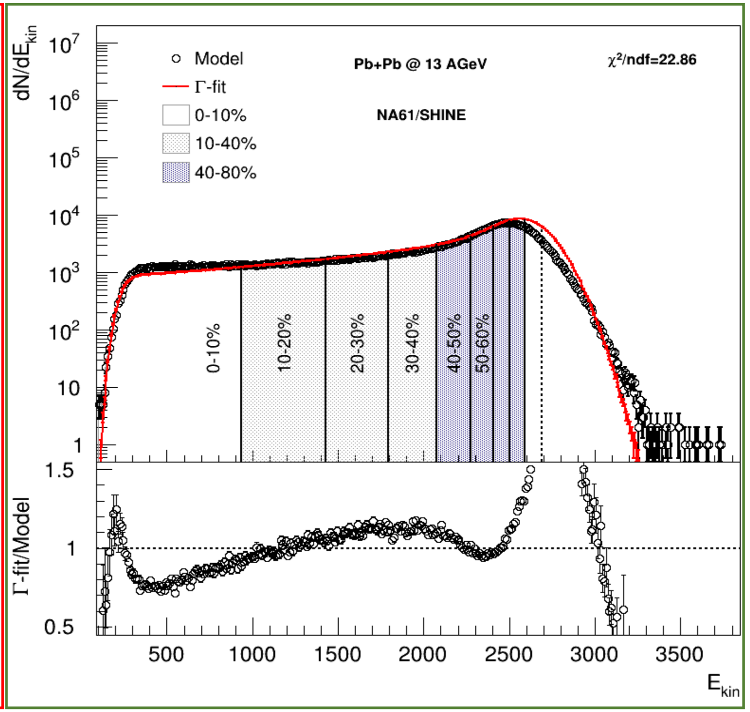


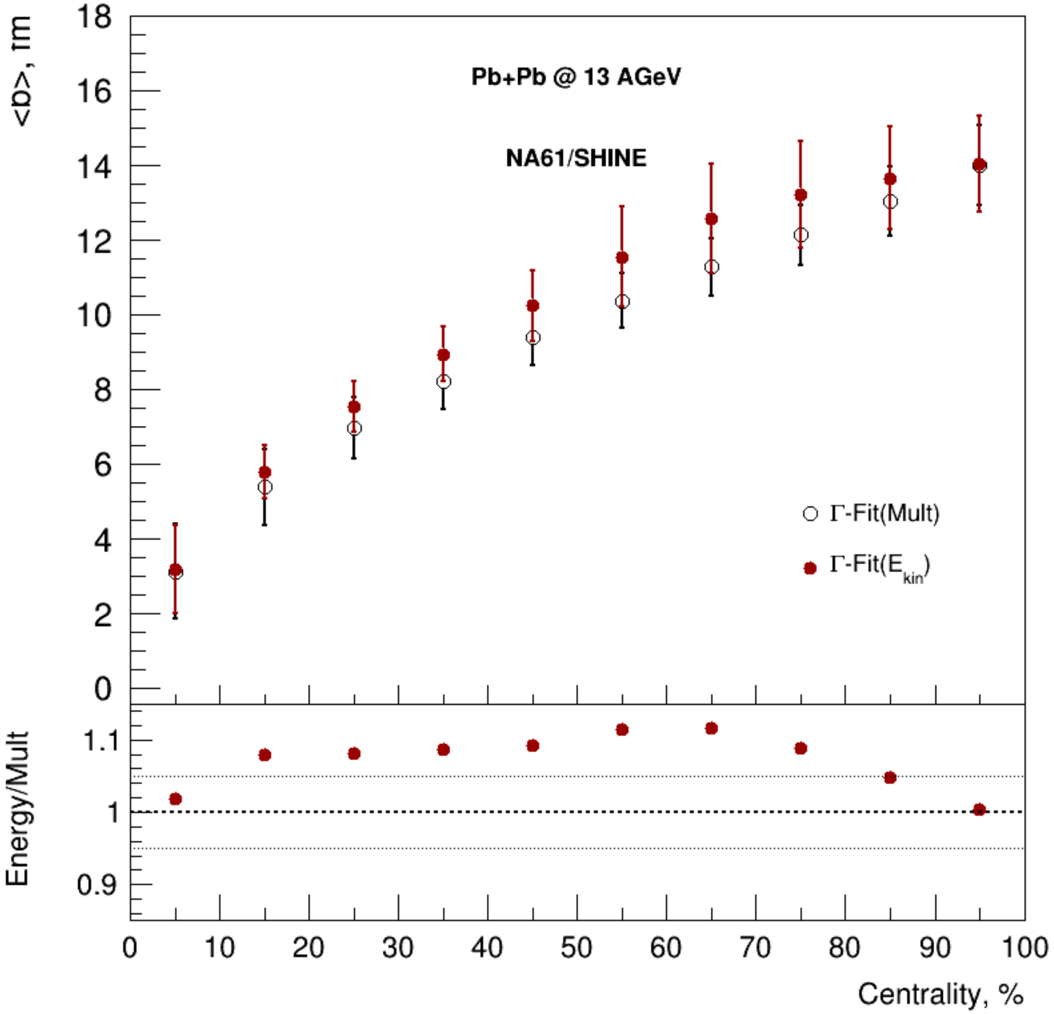
- **Simplified procedure for spectator energy is developed and tested on NA61/SHINE data**
- **Possible improvements are under investigation**

For more details see I.Segal's talk on Cross-PWG 14.02.2023

Centrality determination in MPD using inverse Bayes







- Centrality determination based on spectator energy using inverse Bayes approach is being developed and tested on model (UrQMD, DCM-QGSM-SMM) and NA61/SHINE data
- Possible improvements are under investigation

Application of centrality determination based on spectator energy using MC-Glauber and inverse Bayes apporaches is in progress

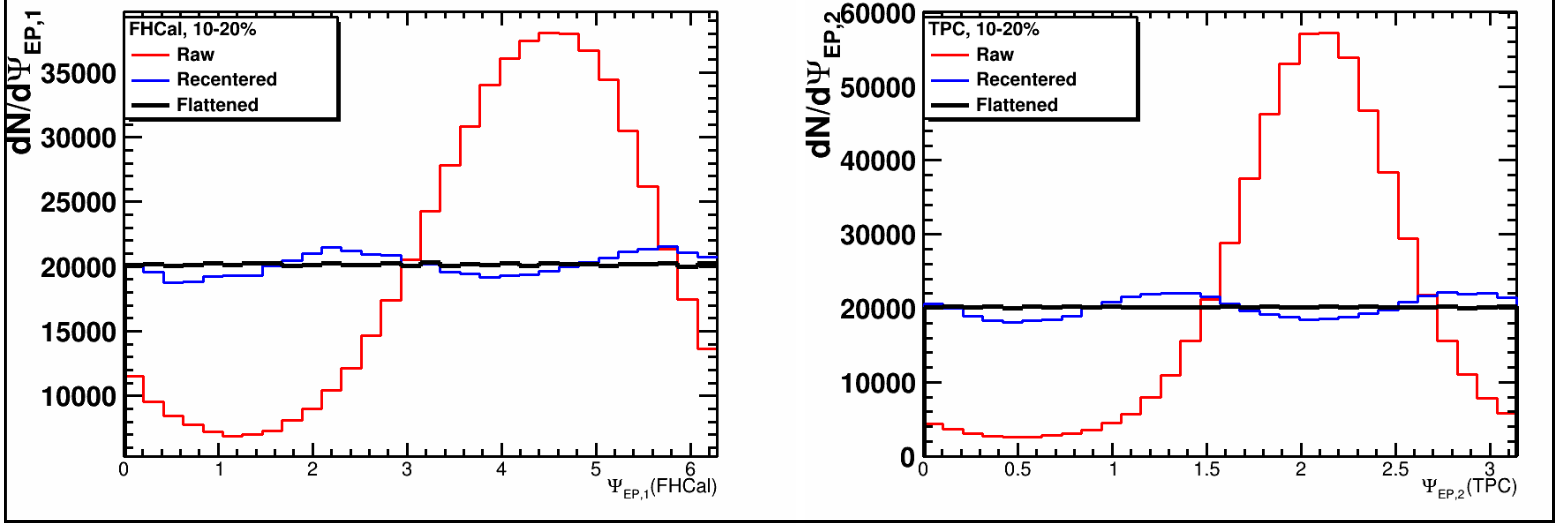
evPlane wagon for EP measurements in MPD

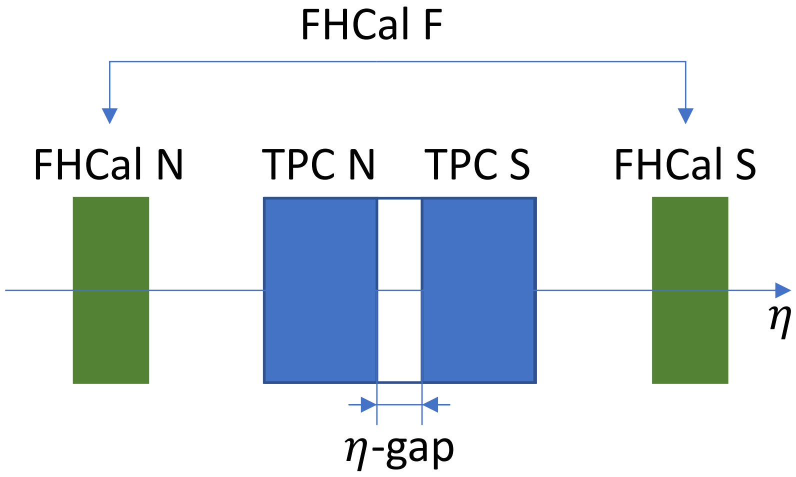
Wagon #1 Wagon #2

AnalysisManager → evCentrality → evPlane

```
MpdAnalysisEvent event
event.getCentrTPC()
event.fMpdEP.GetPhiEP_FHCal_F_all()
event.fMpdEP.GetPhiEP_FHCal_N_all()
event.fMpdEP.GetPhiEP_FHCal_S_all()
event.fMpdEP.GetPhiEP_TPC_N_all()
event.fMpdEP.GetPhiEP_TPC_S_all()
```

EP Corrections are implemented for the future analyses with real data

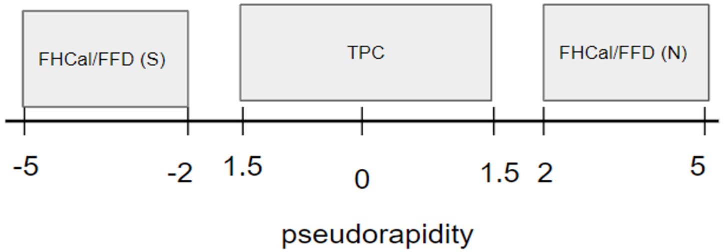




evPlane wagon is implemented into MPD Analysis Framework

See details in P.Parfenov's talk on Cross-PWG 11.04.2023

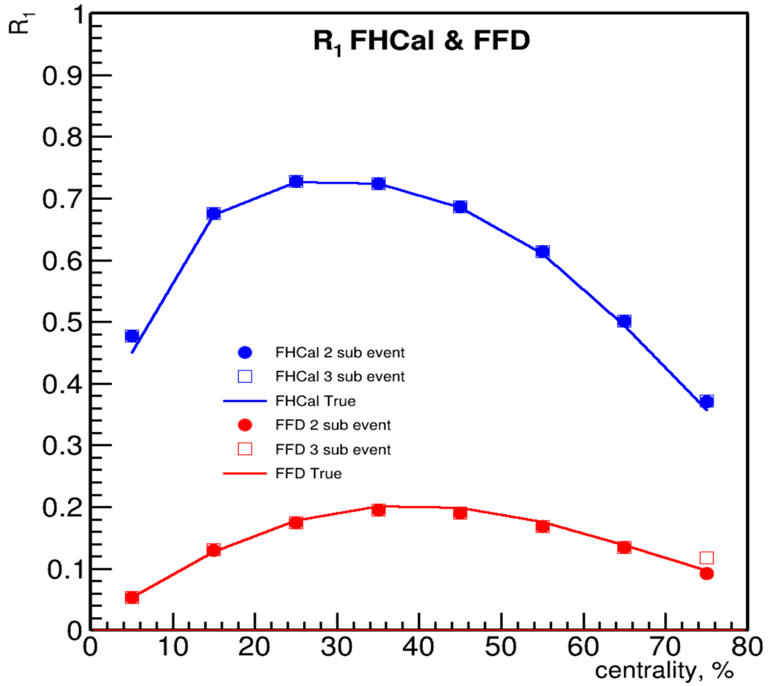
FHCal and FFD comparison for v_n in MPD

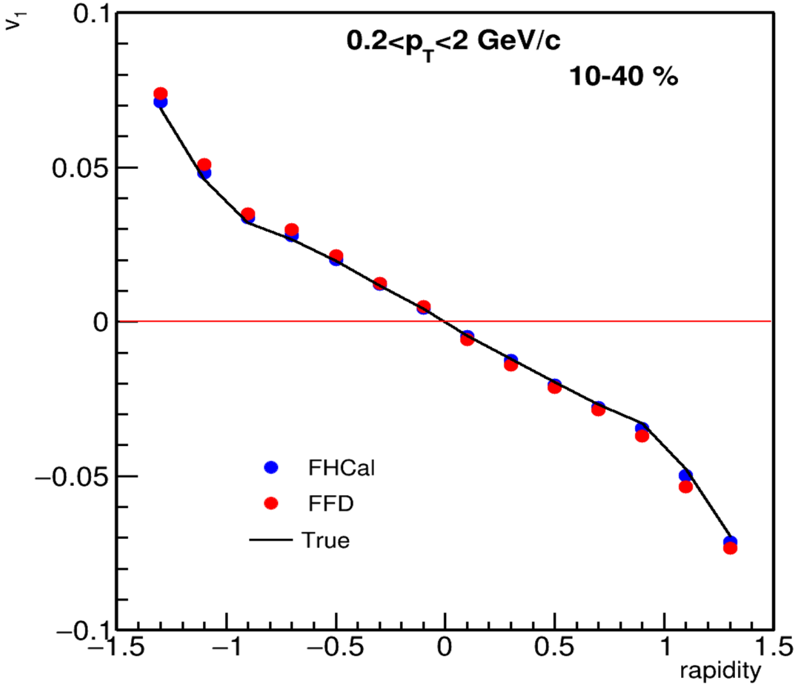


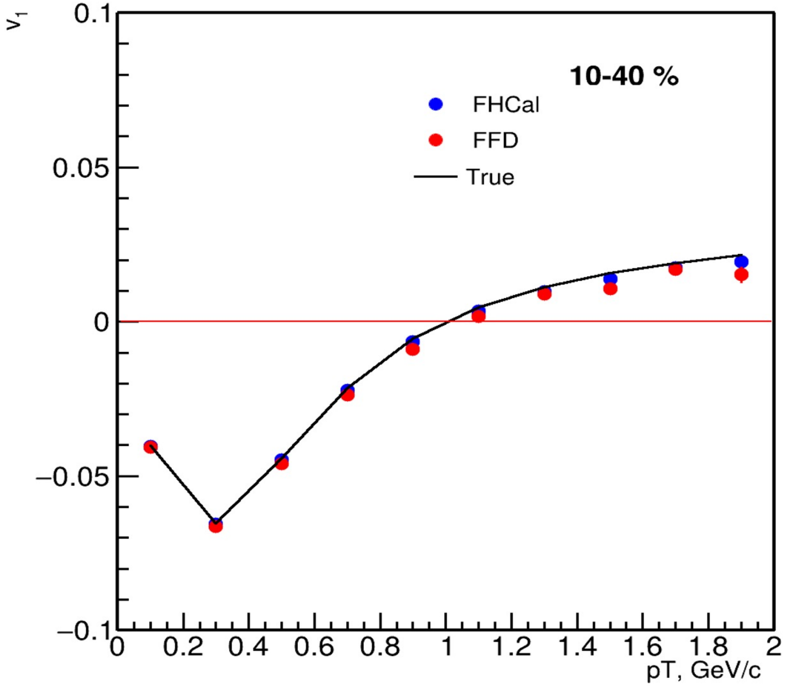
true | 2 sub events | 3 sub events

$$R_{1,i}^{True} = \langle Q_{1,i}\Psi_{RP}\rangle \quad R_{1,i} = \sqrt{\langle Q_{1,i}^{N} Q_{1,i}^{S}\rangle}, i = x, y \quad R_{1,i}^{N} = \sqrt{\frac{2\langle Q_{1,i}^{N} Q_{1,i}^{S}\rangle\langle Q_{1,i}^{S} Q_{1,i}^{TPC}\rangle}{\langle Q_{1,i}^{N} Q_{1,i}^{TPC}\rangle}}$$

See details in V.Troshin's talk on Cross-PWG 14.02.2023





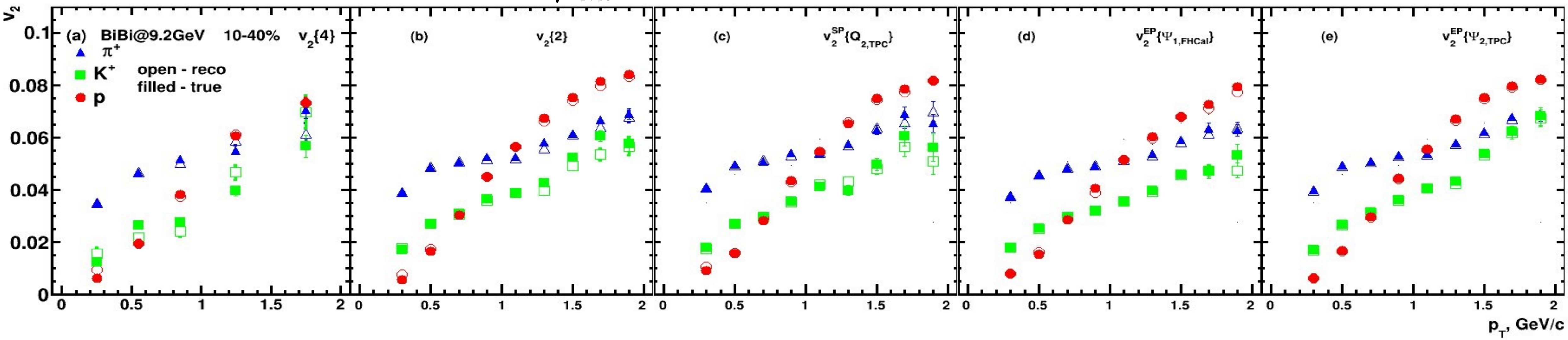


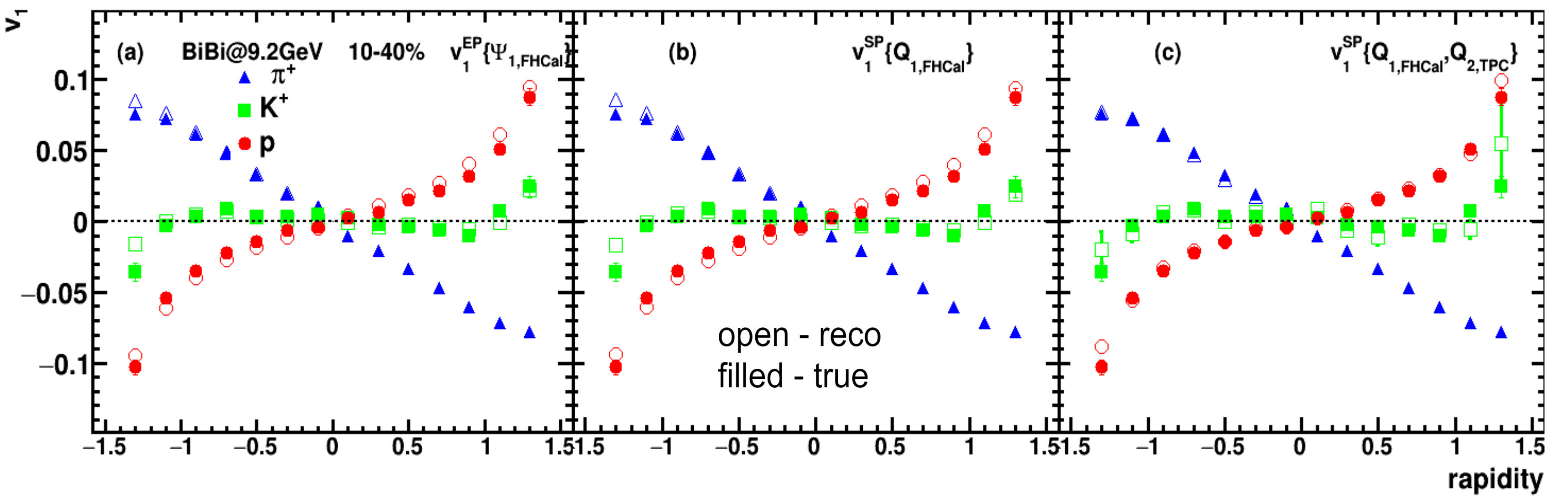
Resolution from FFD is considerably smaller than from FHCal

Flow results using FFD and FHCal are consistent

Performance of $v_{1,2}$ of identified hadrons in MPD

UrQMD, Bi+Bi, $\sqrt{s_{NN}}$=9.2, 10-40%, reconstructed (GEANT4) – production 25





Reconstructed and generated $v_{1,2}$ of identified hadrons have a good agreement for all methods

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

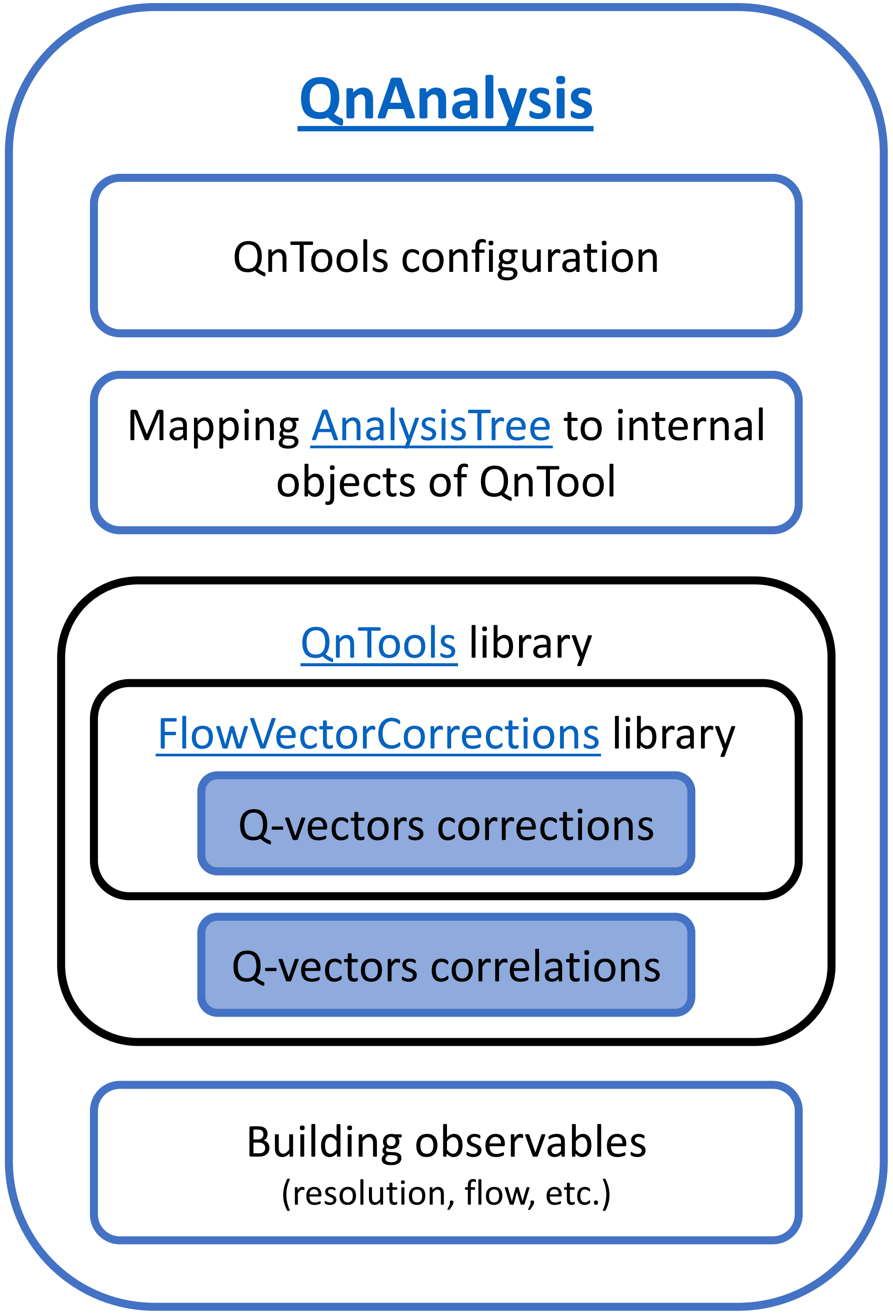
QnAnalysis requirements:

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

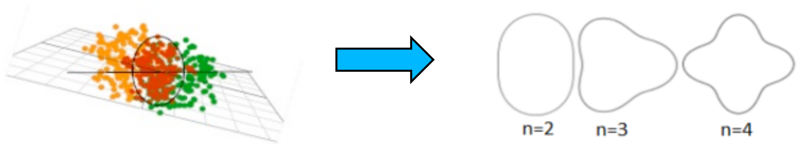
Can be easily installed on NICA cluster using ROOT and CMake modules

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

Continuing to develop implementation of QnTools-based package in MPD

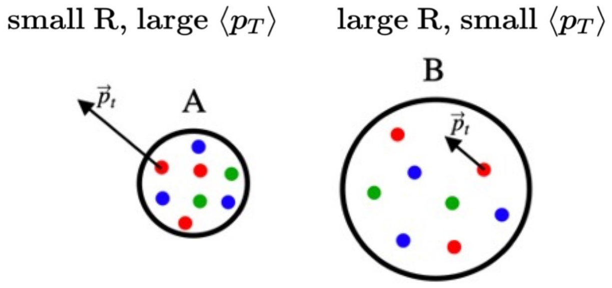


$v_n - [p_T]$ correlation measurements



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

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



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

- 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.)

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

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

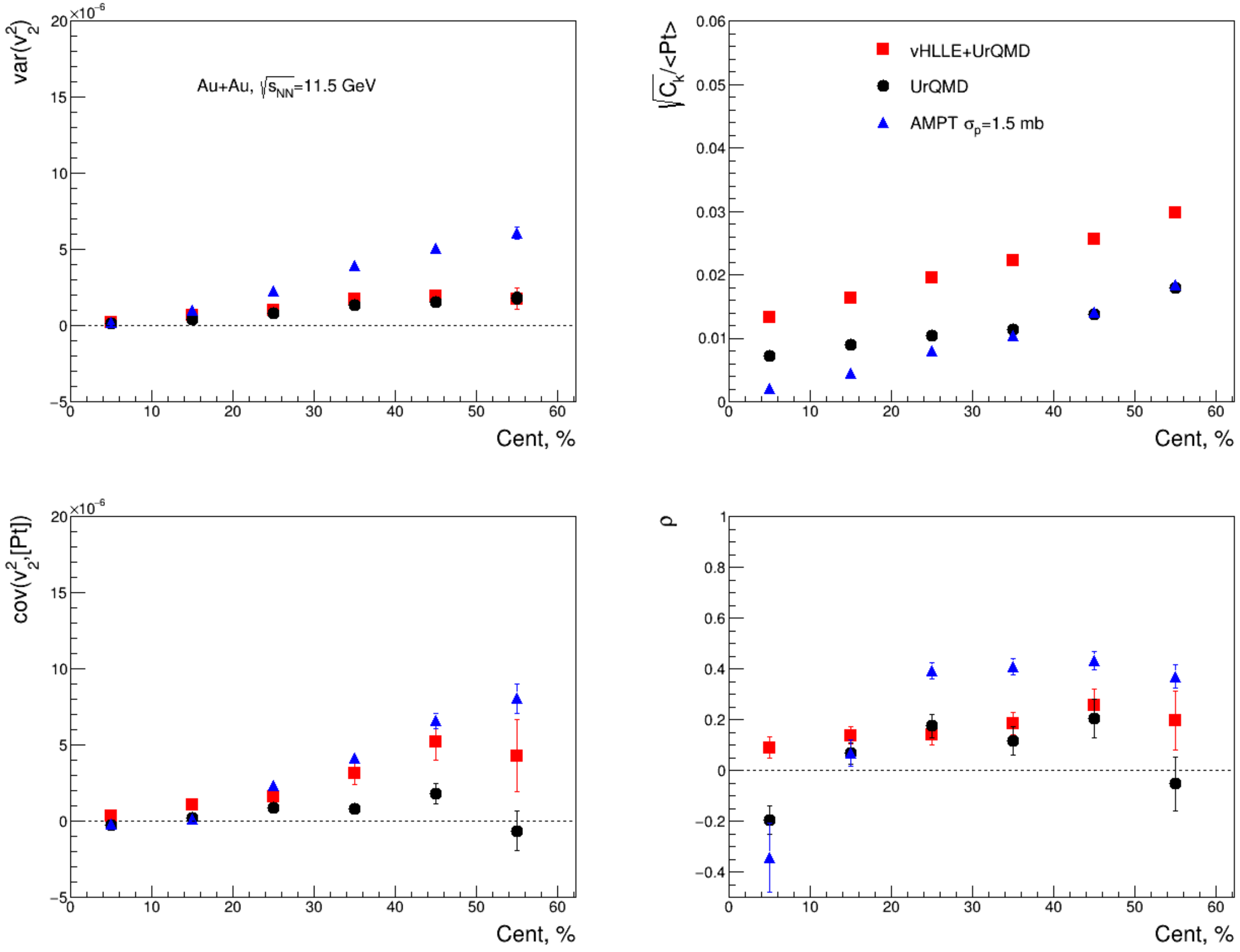
➢The $\rho(\mathrm{v}_2^2, [p_T])$ is sensitive to initial state and its entropy density profile

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

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

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

$v_n - [p_T]$ correlation study in MPD

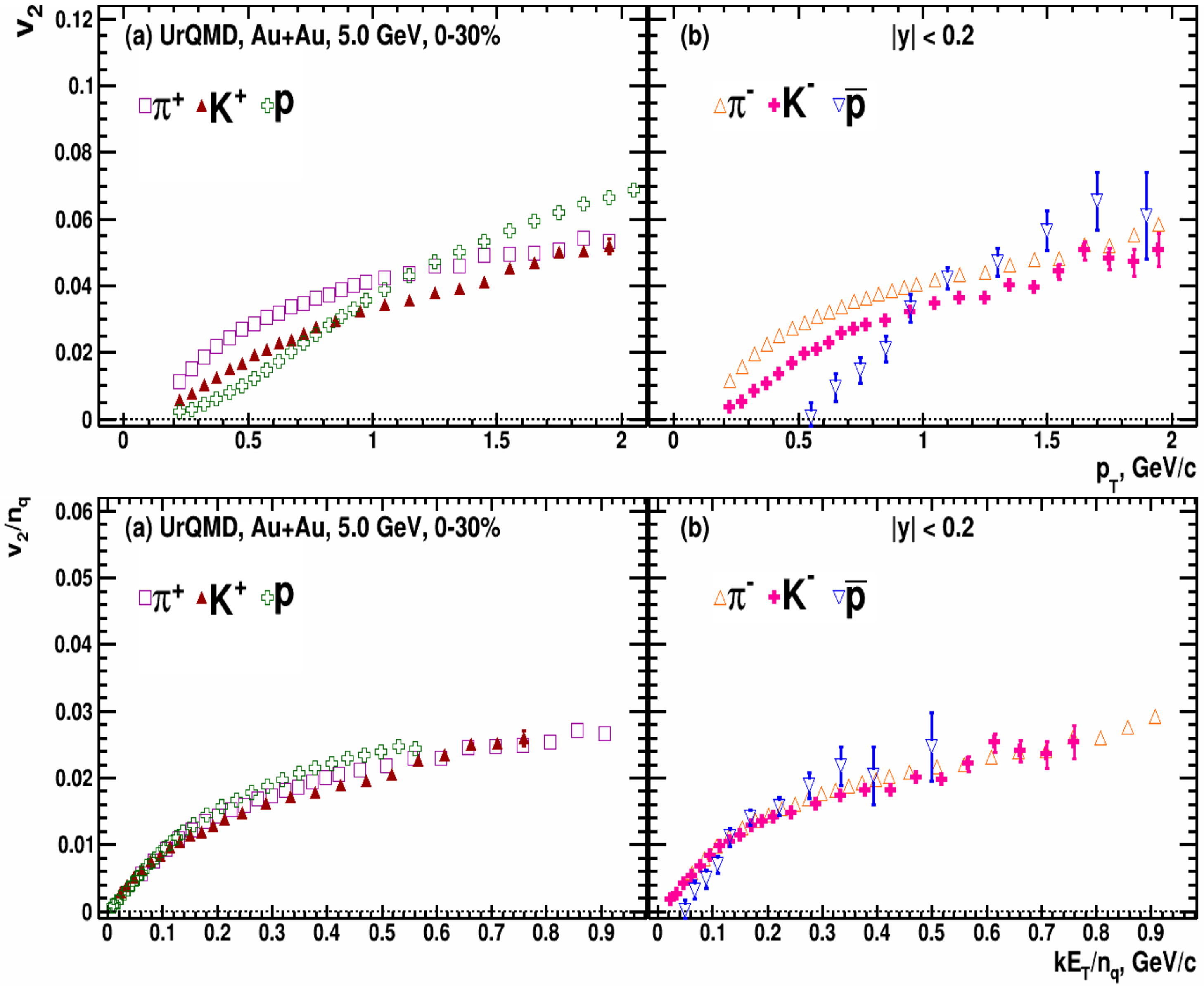


- $\rho(\mathrm{v}_2^2, [p_T])$ decreases in the most central collisions due to the eccentricity decreases faster compared to changes in elliptic area.
- $\rho(\mathrm{v}_2^2, [p_T])$ from vHLLE+UrQMD and UrQMD are consistent with each other due to the same initial state
  - $\rho(\mathrm{v}_2^2, [p_T])$ is sensitive to initial state
- $\mathrm{cov}(\mathrm{v}_2^2, [p_T])$ from vHLLE+UrQMD and AMPT are consistent due to QGP phase
  - $\mathrm{cov}(\mathrm{v}_2^2, [p_T])$ is sensitive to thermalization (η/s, etc.)

See D.Idrisov's talk on Cross-PWG 28.03.2023

Study of $v_n - [p_T]$ correlations can help extract and distinguish information from the initial and final state

NCQ scaling at NICA energies



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

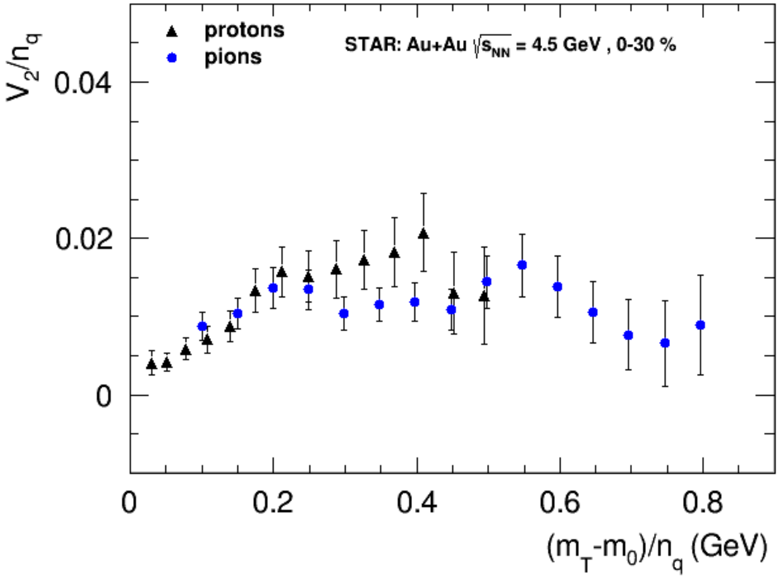
$$n_q = \begin{cases} 2 \text{ for mesons} \\ 3 \text{ for baryons'} \end{cases} \qquad KE_T = \sqrt{m^2 + p_T^2} - m$$

Generally, it is to be believed NCQ scaling impies partonic collectivity

However, UrQMD with cascade mode reproduces mass ordering and NCQ scaling at NICA energies

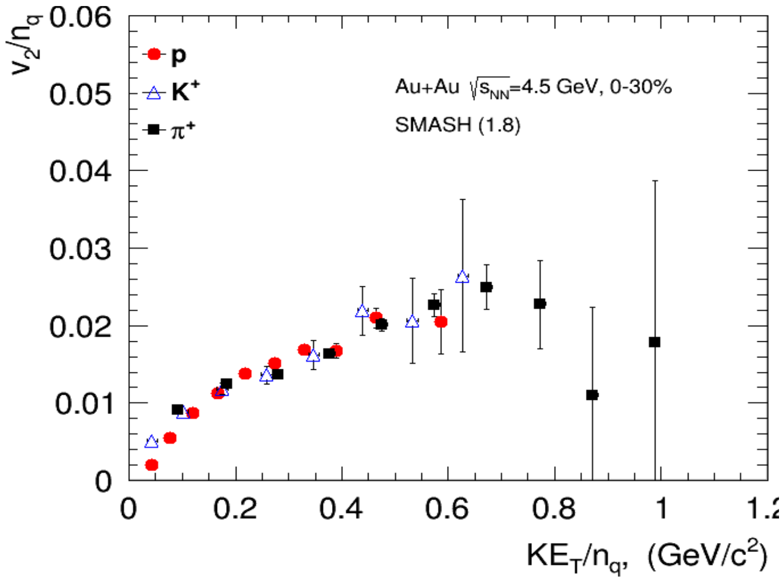
Additional indicators should be checked to make conclusions about partonic or hadronic collectivity

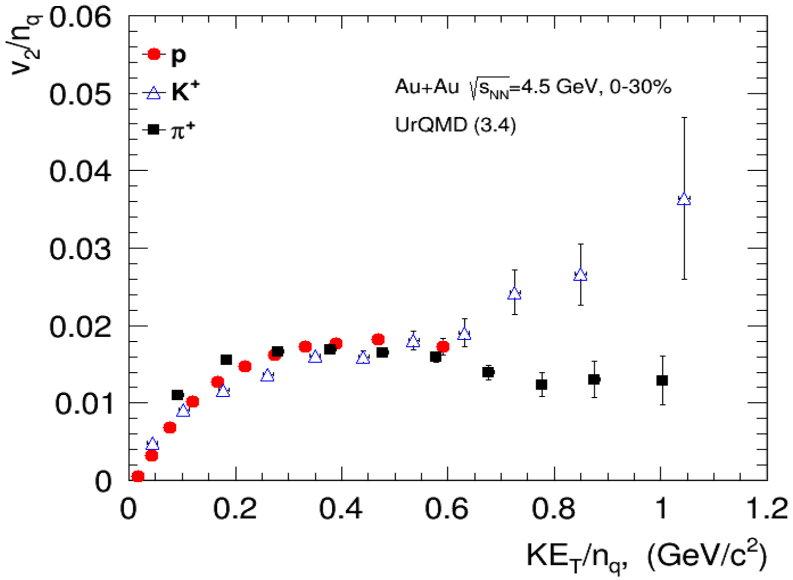
NCQ scaling at NICA energies

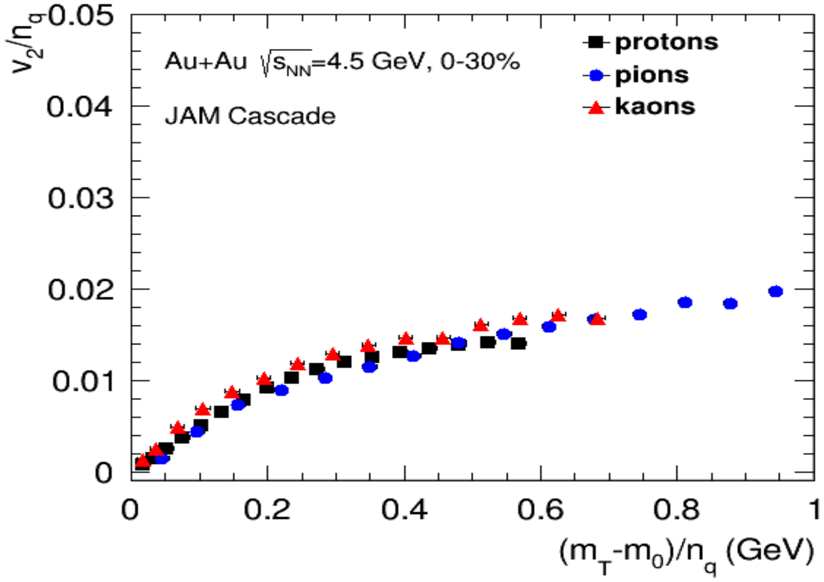


- Scaling holds up at 4.5 GeV in STAR data and pure string/hadronic cascade models (without partonic d.o.f.)

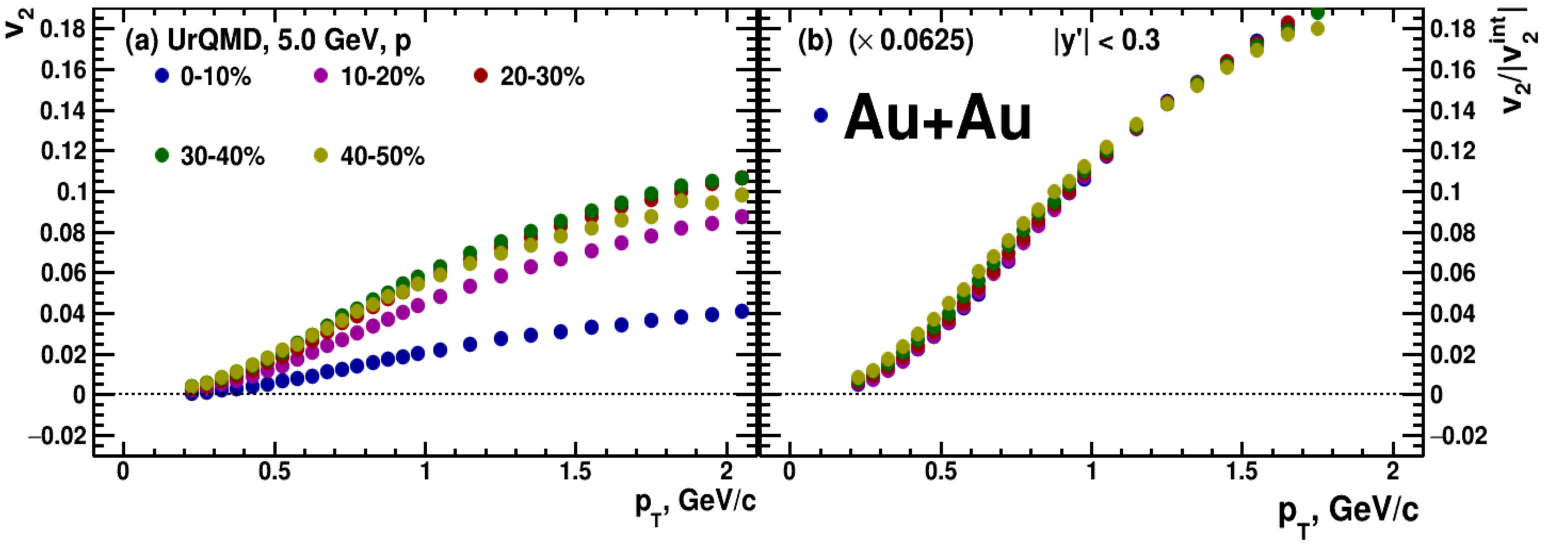
KE_T/n_q scaling at 4.5 GeV might be accidental – more careful studies should be performed

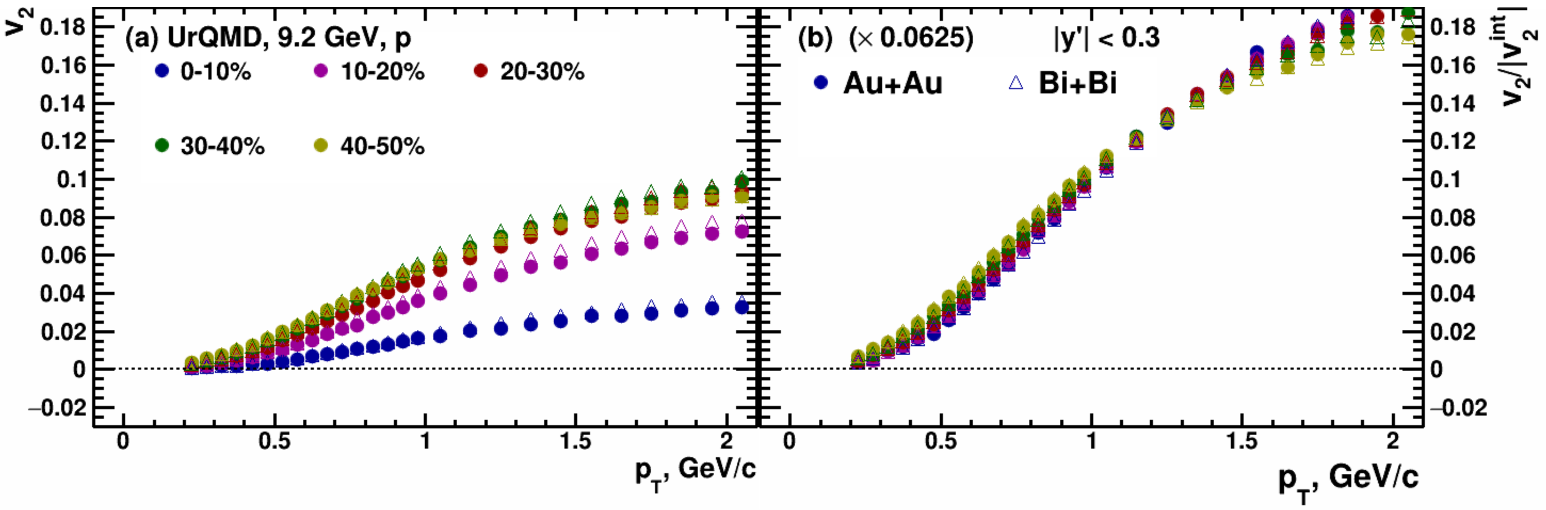






Scaling with integral anisotropic flow

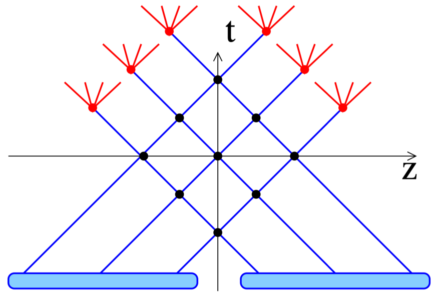




$$\left|v_n^{int}\right| = \left|\langle v_n(p_T, y, \text{centrality})\rangle_{p_T,y}\right|$$

Scaling works for UrQMD model at $\sqrt{s_{NN}} = 5 - 9.2$ GeV for Au+Au and Bi+Bi systems

EPOS4 model

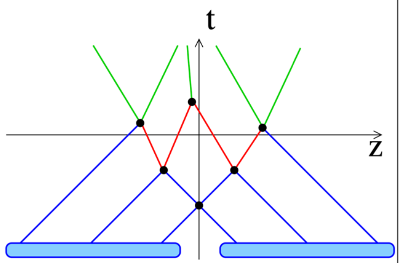


A+A collision at high energy

Collision zone pointlike

High energies ($\sqrt{s_{NN}} \gg 1$ GeV):

<u>"Parallel approach":</u> all interactions are done simultaneously via S-matrix theory, hadron production comes later

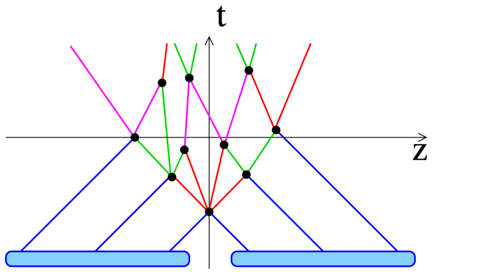


A+A collision at intermediate energy

Red/green lines: produced hadrons

Intermediate energies ($4 < \sqrt{s_{NN}} < 24$ GeV):

<u>"Partially parallel aproach":</u> some NN scatterings are realized before particle production



A+A collision at low energy
red/green/magenta lines: produced hadrons

Low energies ($\sqrt{s_{NN}} < 4$ GeV):

<u>"Cascade approach":</u> all interactions are done in sequence together with particle production

Main idea behind the EPOS model:

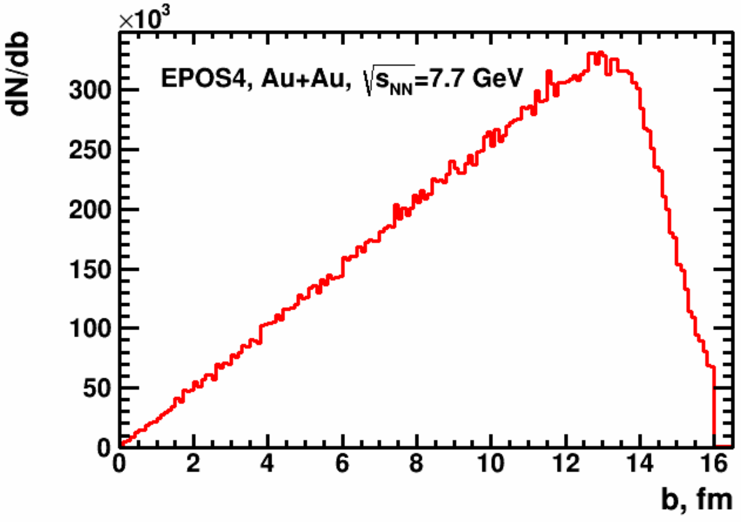
- **Provide a "complete" event generator with a consistent overall picture from low to high energies.**

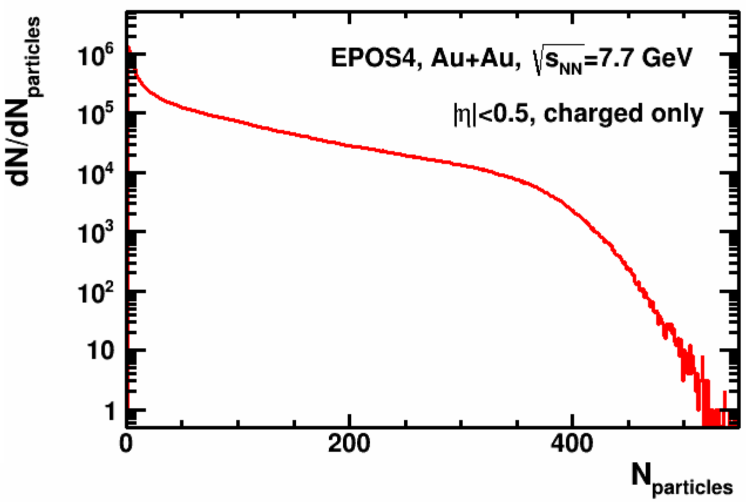
EPOS4 generation scheme:

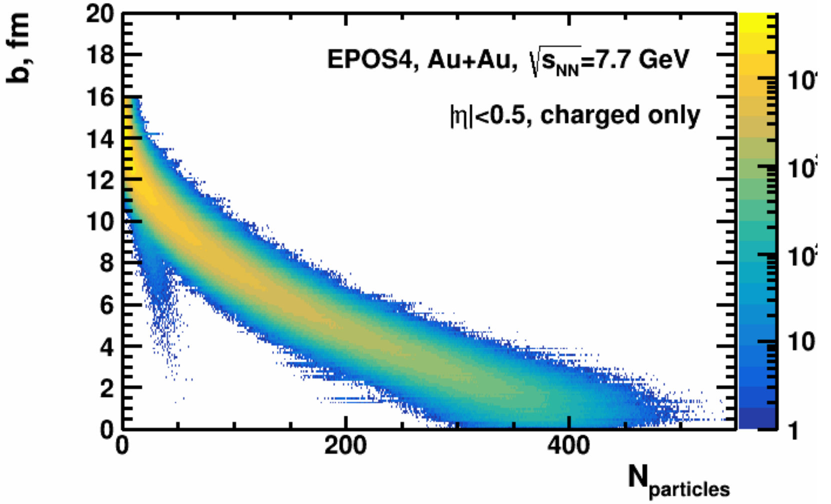
- Primary interactions (3 approaches)
- Secondary interactions:
  - Core-corona separation procedure
  - Hydrodynamic evolution
  - Microcanonical hadronization

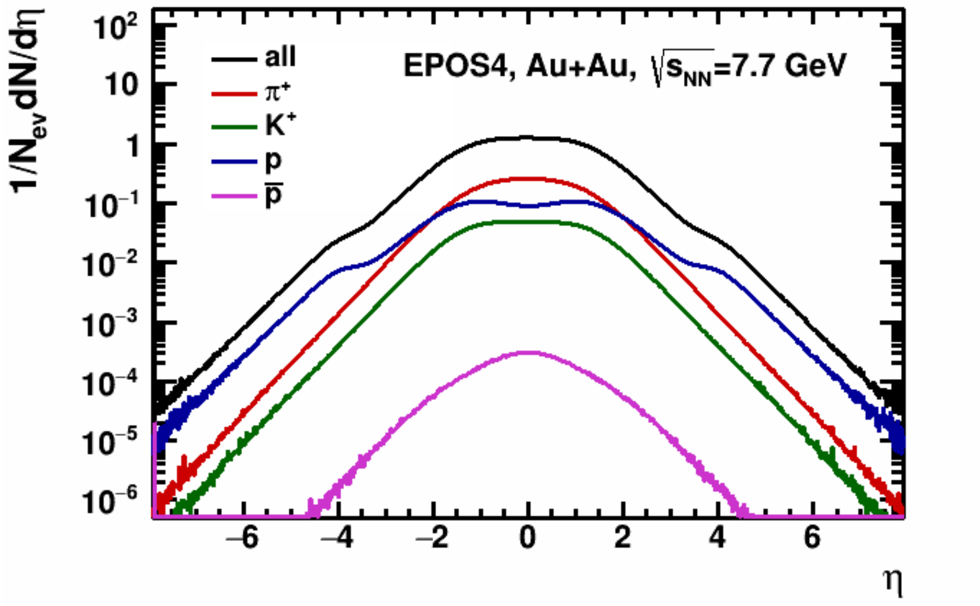
K. Werner, arXiv:2301.12517 [hep-ph] (2023)

EPOS4 model: first look









30 M min bias events were generated for Au+Au $\sqrt{s_{NN}}$=7.7 GeV with x3ff EoS (with vHLLE hydro model)

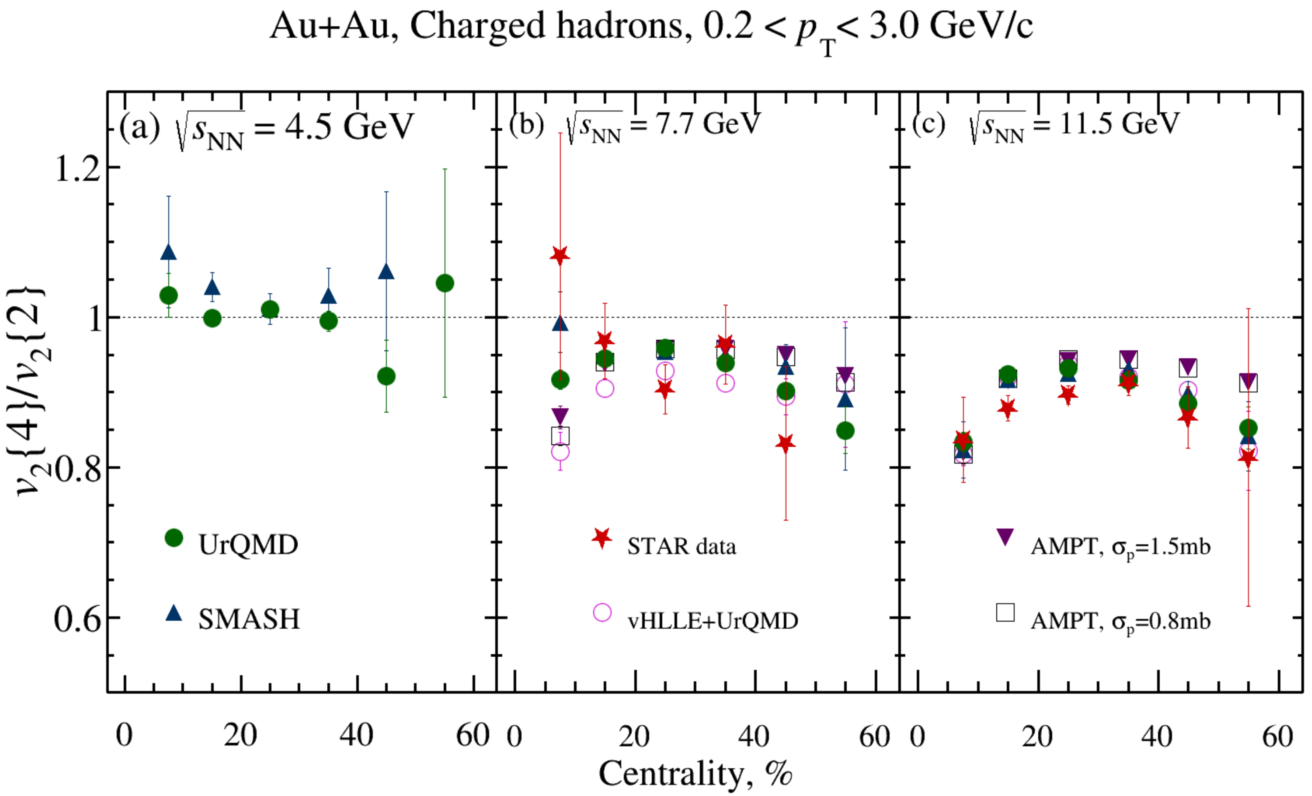
Further investigations are in progress

Summary and Outlook

- **Centrality determination procedures in MPD:**
  - Centrality determination using spectator energy is being developed using both MC-Glauber and inverse Bayes approaches
  - Further improvements are in progress
- **Development of the unified MPD Analysis Framework:**
  - evPlane wagon for EP measurements was implemented in the mpdroot and is ready for use
  - Wagon for v_n measurements will be implemented in the future
- **Feasibility study for anisotropic flow:**
  - Comparison of EP resolution and v_n using FFD and FHCal symmetry planes was done
  - v_n of identified charged hadrons: results from reconstructed and generated data are in a good agreement for all methods
- **Relative elliptic flow fluctuations at lower NICA energies is being studied:**
  - More statistics needed to make comparison of $v_2\{4\} / v_2\{2\}$ protons and antiprotons
- $\boldsymbol{v_n - [p_T]}$ **correlations can help extract and distinguish information from the initial and final state**
- **Beam energy dependence of anisotropic flow:**
  - NCQ scaling holds for cascade models at NICA energies – one should provide additional indicators to make conclusions about partonic or hadronic collectivity
  - First look at the new major version of EPOS (EPOS4)
  - New vHLLE+UrQMD mass production request is being prepared

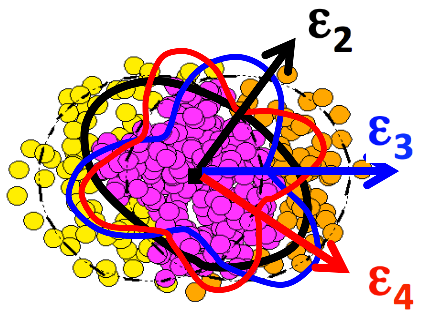
Backup slides

Relative flow fluctuations of charged hadrons



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

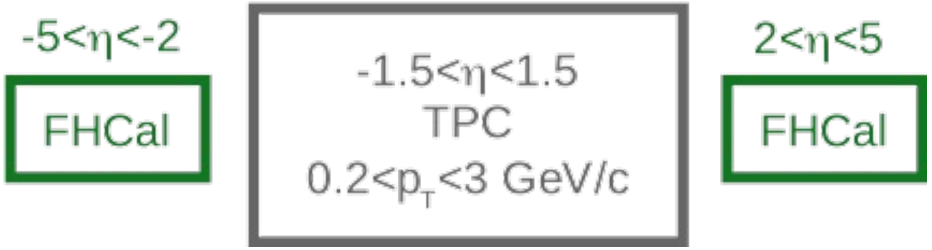
- Relative v_2 fluctuations ($v_2\{4\}/v_2\{2\}$) observed by STAR experiment can be reproduced both in the string/cascade models (UrQMD, SMASH) and model with QGP phase (AMPT SM, vHLLE+UrQMD)
- Dominant source of v_2 fluctuations: **participant eccentricity fluctuations** in the initial geometry
- Are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

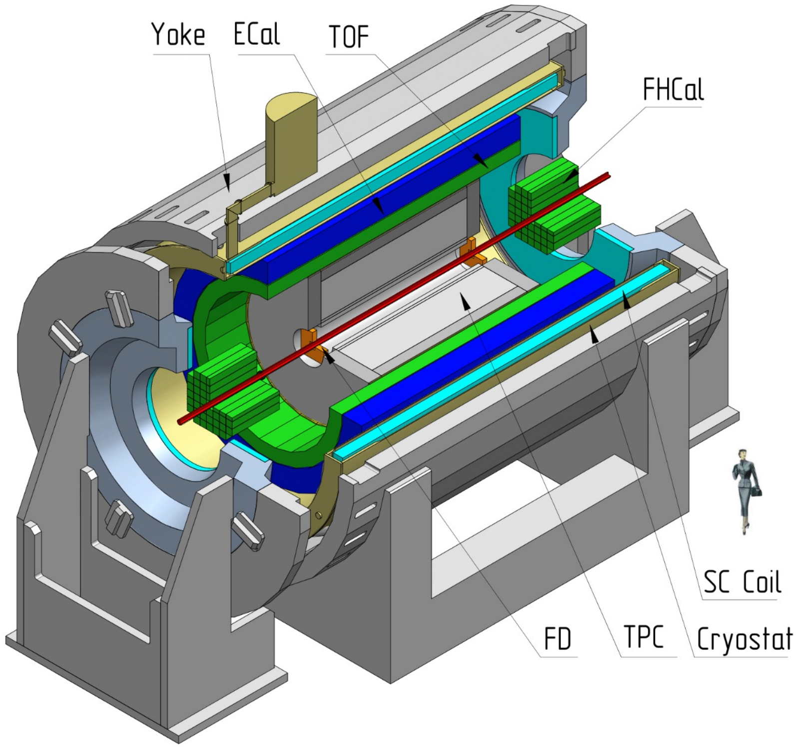


MPD Experiment at NICA

UrQMD → GEANT4 → Reconstruction → Flow analysis

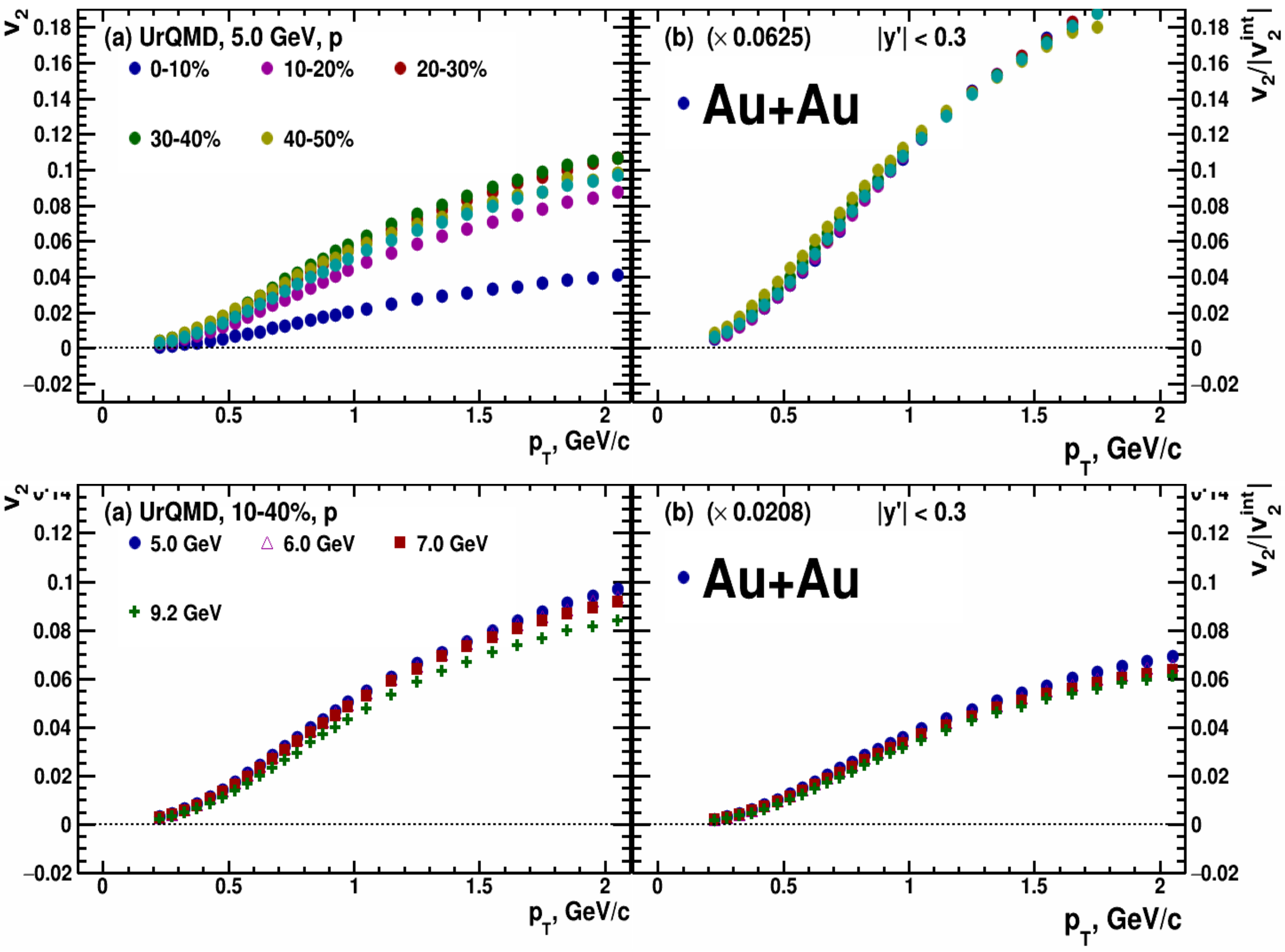
- Bi+Bi: 50M at $\sqrt{s_{NN}}$ = 9.2 GeV (prod. 25)
- Centrality determination: Bayesian inversion method and MC-Glauber
- Event plane determination: TPC, FHCal
- Track selection:
  - Primary tracks
  - $N_{TPC\ hits} \geq 16$
  - $0.2 < p_T < 3.0$ GeV/c
  - $|\eta| < 1.5$
  - PID – ToF + dE/dx





Multi-Purpose Detector (MPD) Stage 1

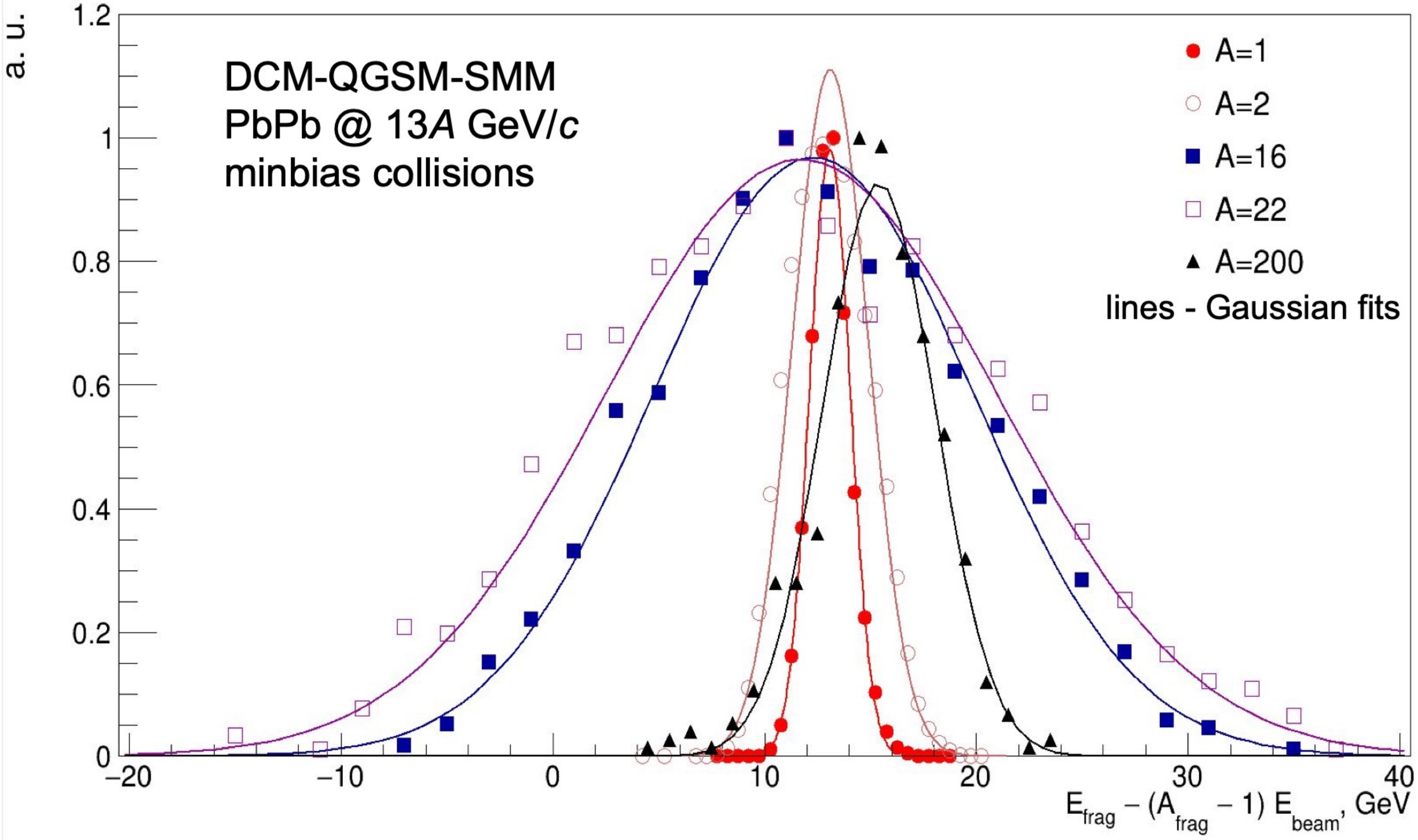
Scaling with integral anisotropic flow



$$|v_n^{int}| = |\langle v_n(p_T, y, \text{centrality})\rangle_{p_T,y}|$$

Scaling works for UrQMD model at $\sqrt{s_{NN}} = 5 - 9.2$ GeV

Gaussian approximation for fragments energy



- Distribution of mass numbers of spectators fragments could be fitted by Gauss distribution
- Mean values equal to product of beam energy and fragment's mass
- Total spectators energy distribution is also Gauss:

$$P(E_{tot}; \mu_{tot}, k_{tot}) \approx \prod_{i=1}^{N_{spec}} P(E^{i}_{spec}; \mu_{spec}, k_{spec})$$

- Measured energy distribution follows convolution of two Gauss distributions (sum of fragments energy and detector response)