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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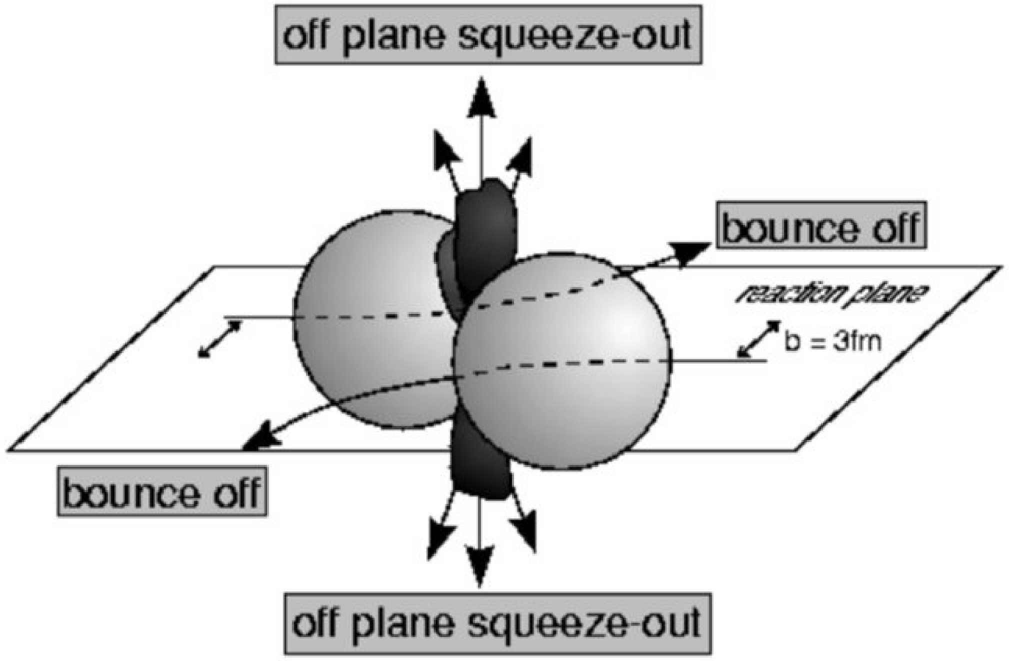
For the MPD Collaboration

XII MPD Collaboration Meeting, Belgrade, Serbia, 2-6 October 2023

This work is supported by: the NRNU program Priority 2030 and
Special Purpose Funding Programme within the NICA Megascience Project in 2023

Anisotropic flow at NICA energies



Azimuthal distribution of produced particles with respect to RP:

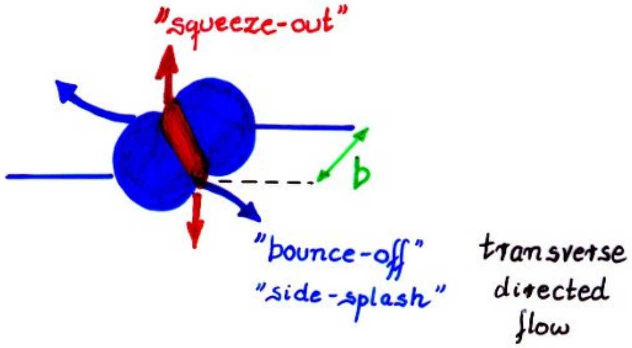
$$\rho(\varphi - \Psi_{RP}) = \frac{1}{2\pi}\left(1 + 2\sum_{n=1}^{\infty} v_n \cos n(\varphi - \Psi_{RP})\right)$$

Coefficients of the decomposition are referred to as collective flow

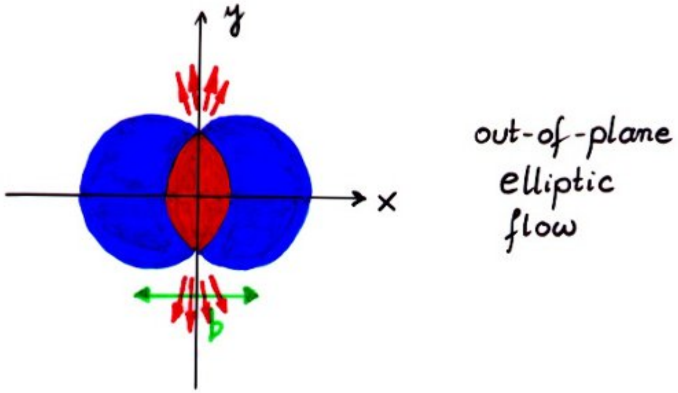
$$v_n = \langle \cos\left[n(\varphi - \Psi_{RP})\right]\rangle$$

v_1 is called directed and v_2 is called elliptic flow

Bounce-off



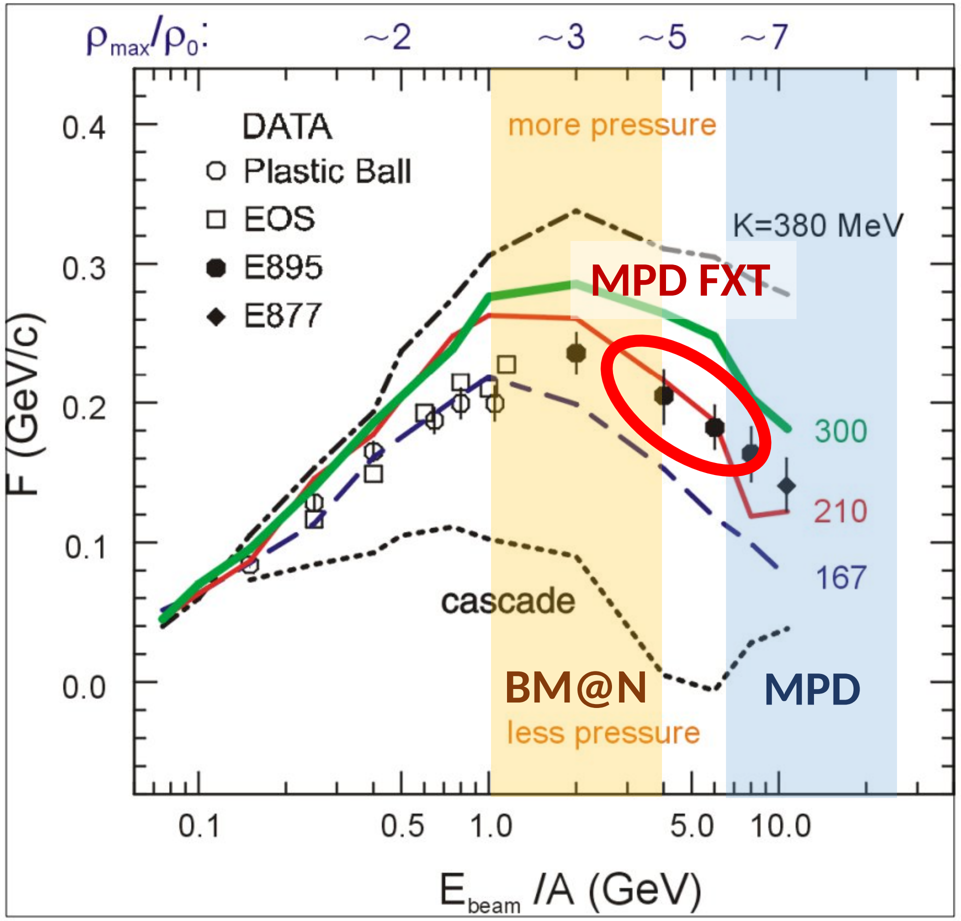
Squeeze-out

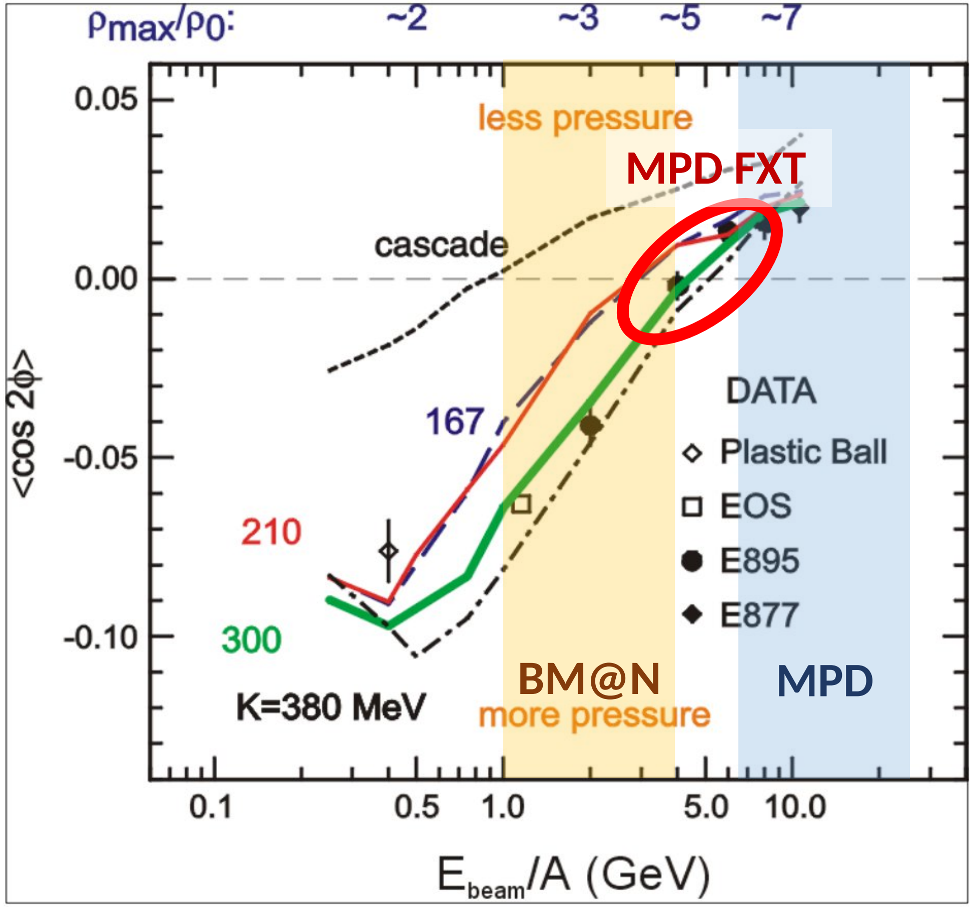


Collective flow is sensitive to:

- Compressibility of the created in the collision matter ($t_{exp} = R/c_s$, $c_s = c\sqrt{dp/d\varepsilon}$)
- Time of the interaction between the matter within the overlap region and spectators ($t_{pass} = 2R/\gamma_{CM}\beta_{CM}$)

Sensitivity of anisotropic flow to EoS at NICA energies

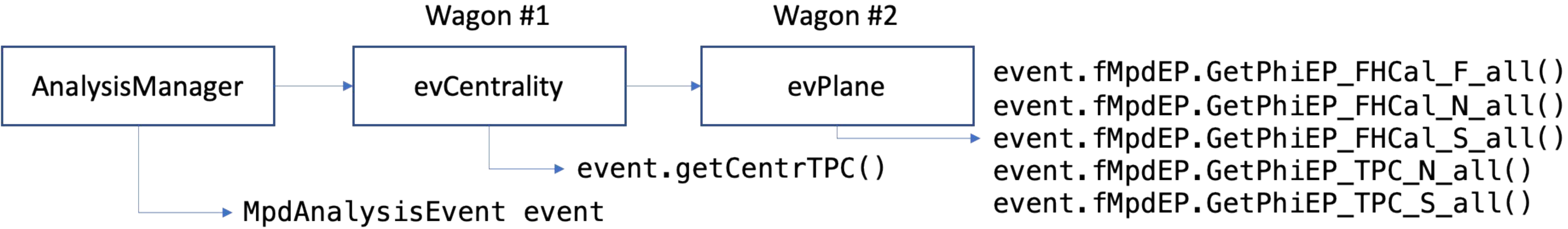


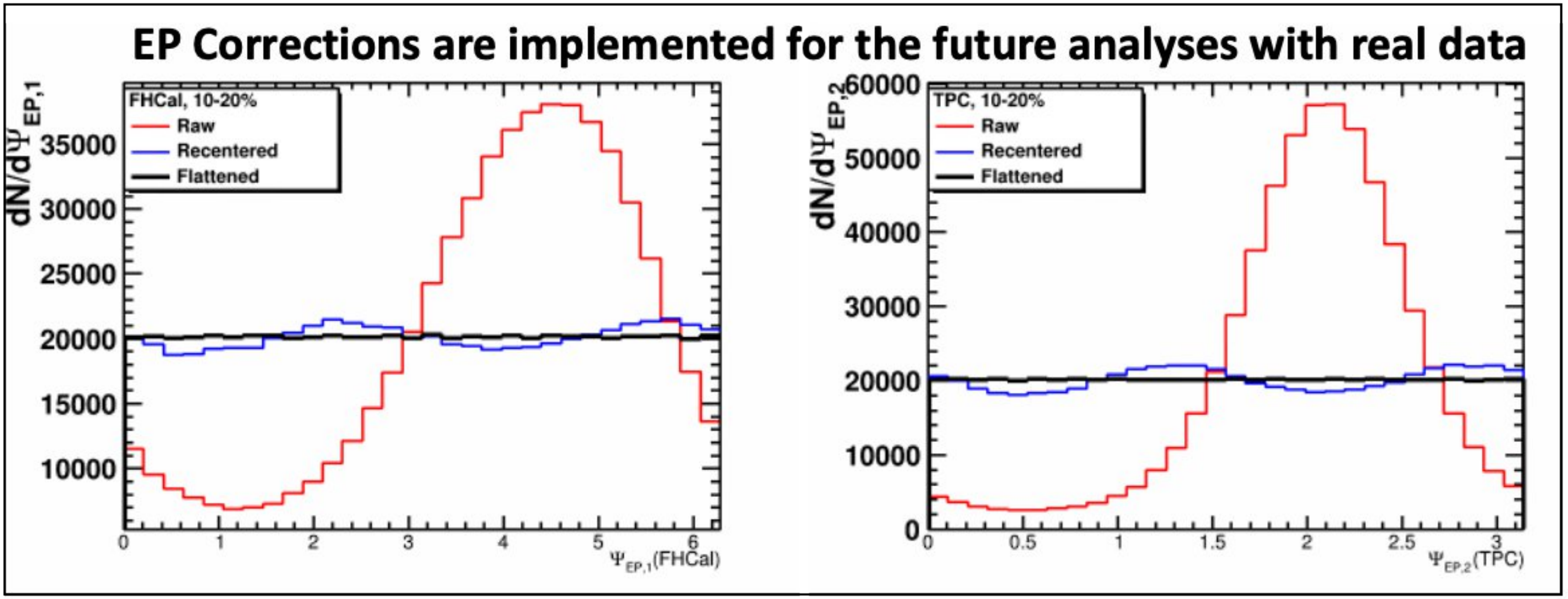


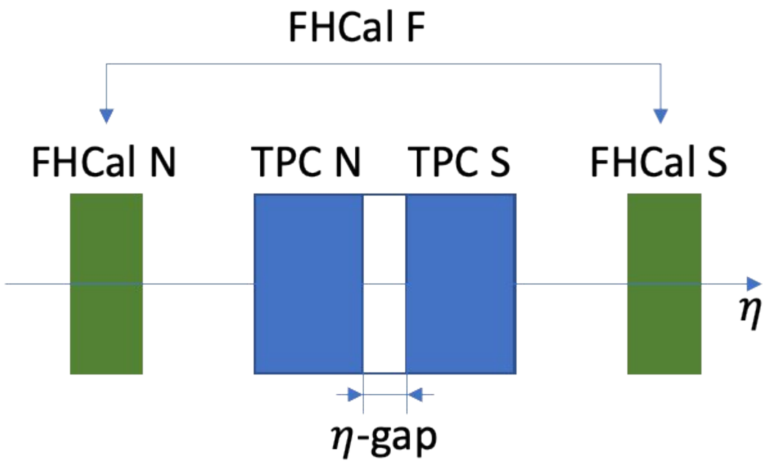
P. DANIELEWICZ, R. LACEY, W. LYNCH
10.1126/science.1078070

- **The flow data from E895 experiment have ambiguous interpretation:**
  v_1 suggests soft EOS while v_2 corresponds to hard EOS
- **Additional measurements are essential to clarify the previous measurements**

evPlane wagon for EP measurements in MPD

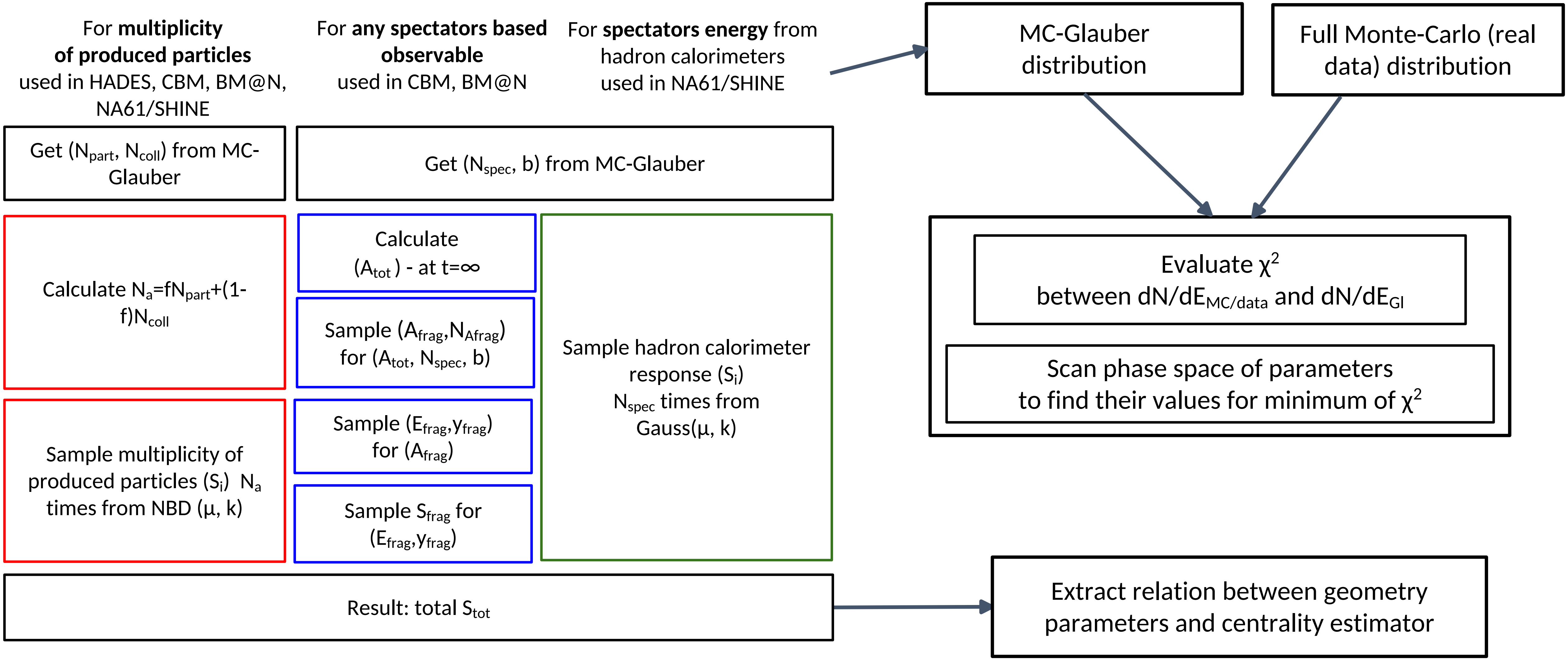






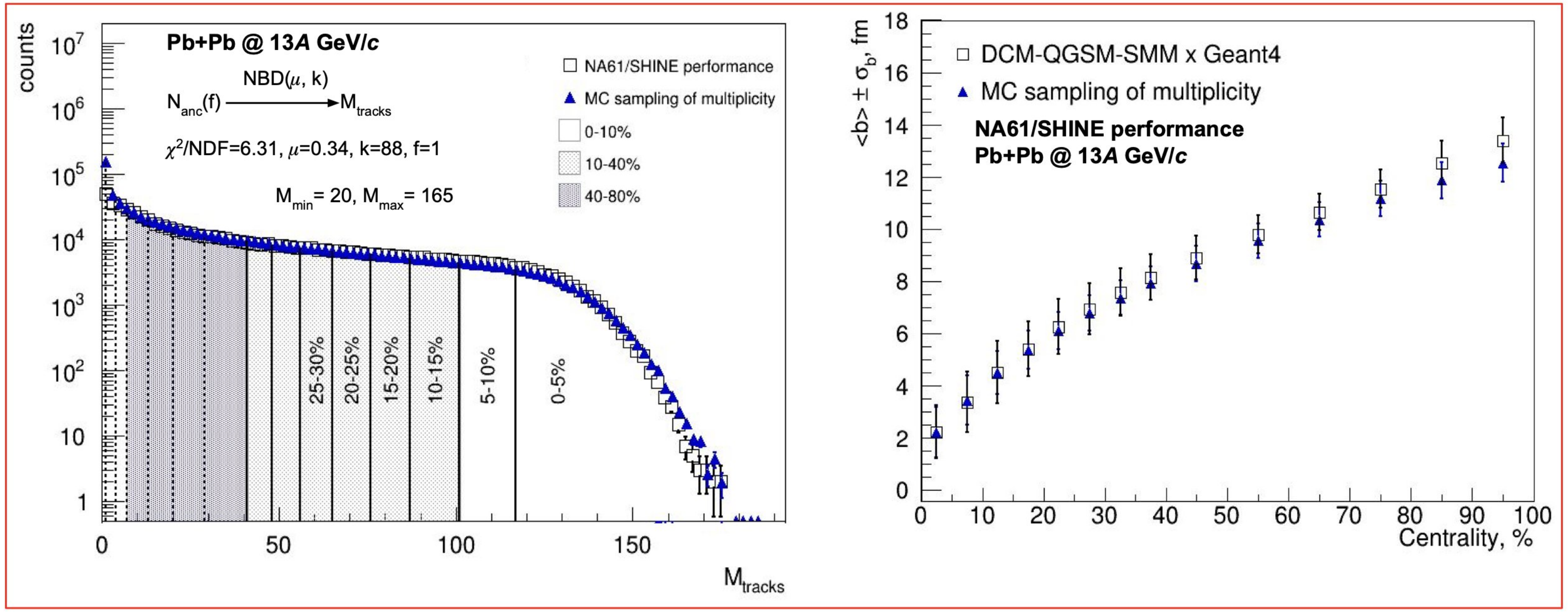
- **evPlane wagon is implemented into MPD Analysis Framework and is already being used in the collaboration**
- **Wagon for the flow measurements (Event Plane method) is on its way**

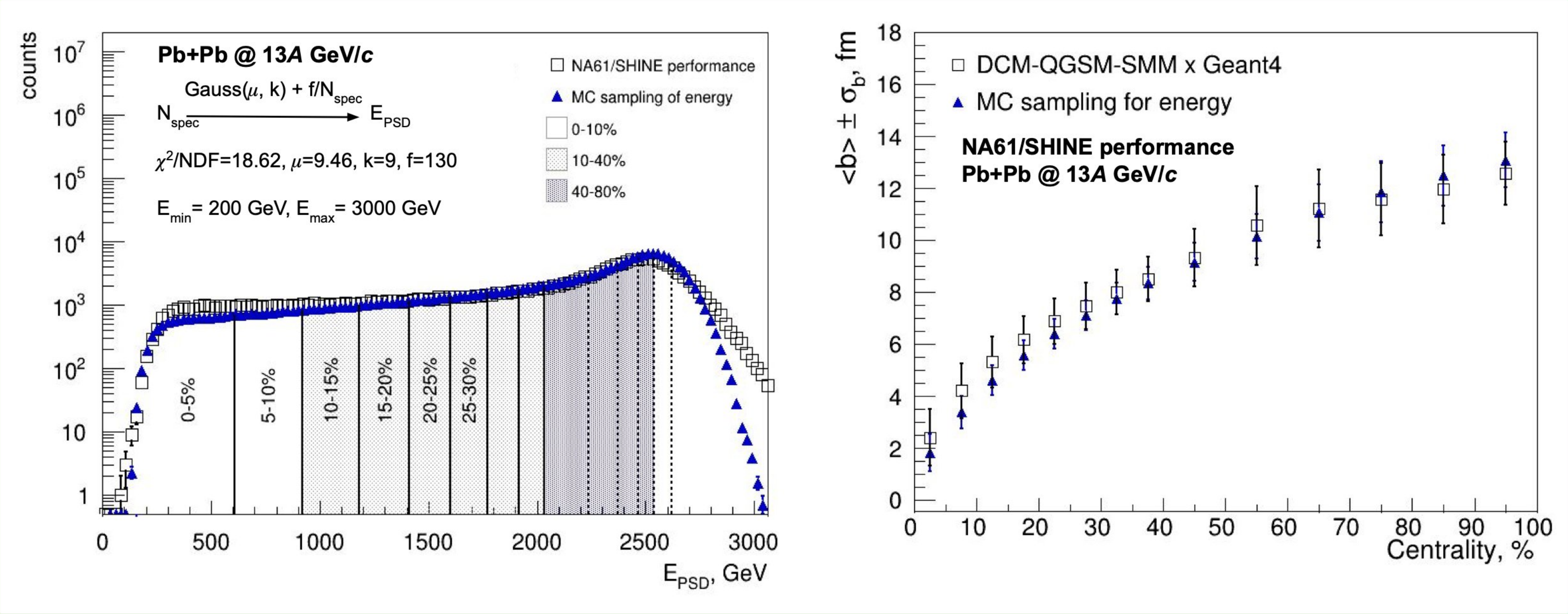
Centrality determination based on Monte-Carlo sampling



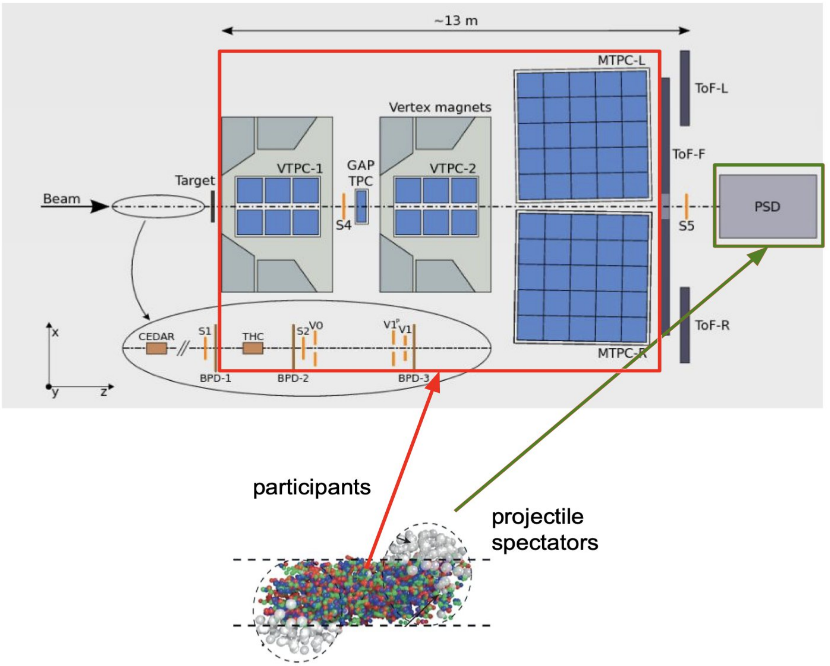
Centrality can be estimated based on multiplicity of produced charged particles or spectator energy

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**

The Bayesian inversion method (Γ-fit): main assumptions

Relation between multiplicity N_{ch} and impact parameter b

is defined by the fluctuation kernel:

$$P(E \mid c_b) = \frac{1}{\Gamma(k(c_b))\theta^2} E^{k(c_b)-1} e^{-E/\theta}$$

$$\theta = \frac{D(E)}{\langle E \rangle}, \quad k = \frac{\langle E \rangle}{\theta}$$

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

$\langle E \rangle, \quad D(E)$ – average value and variance of energy

$$\langle E \rangle = \mu_1 \langle E'(c_b) \rangle + \lambda_1, \quad D(E) = \mu_2 D(E'(c_b))$$

Three fit parameters μ_1, μ_2, λ_1

$\langle E'(c_b) \rangle, \quad D(E'(c_b))$ – average value and variance of energy from the model

These quantities can be approximated by polynomials

$$\langle E'(c_b) \rangle = \sum_{j=1}^{8} a_j c_b^j, \quad D(E'(c_b)) = \sum_{j=1}^{6} b_j c_b^j$$

2 main steps of the method:

Fit experimental (model) distribution with P(E)

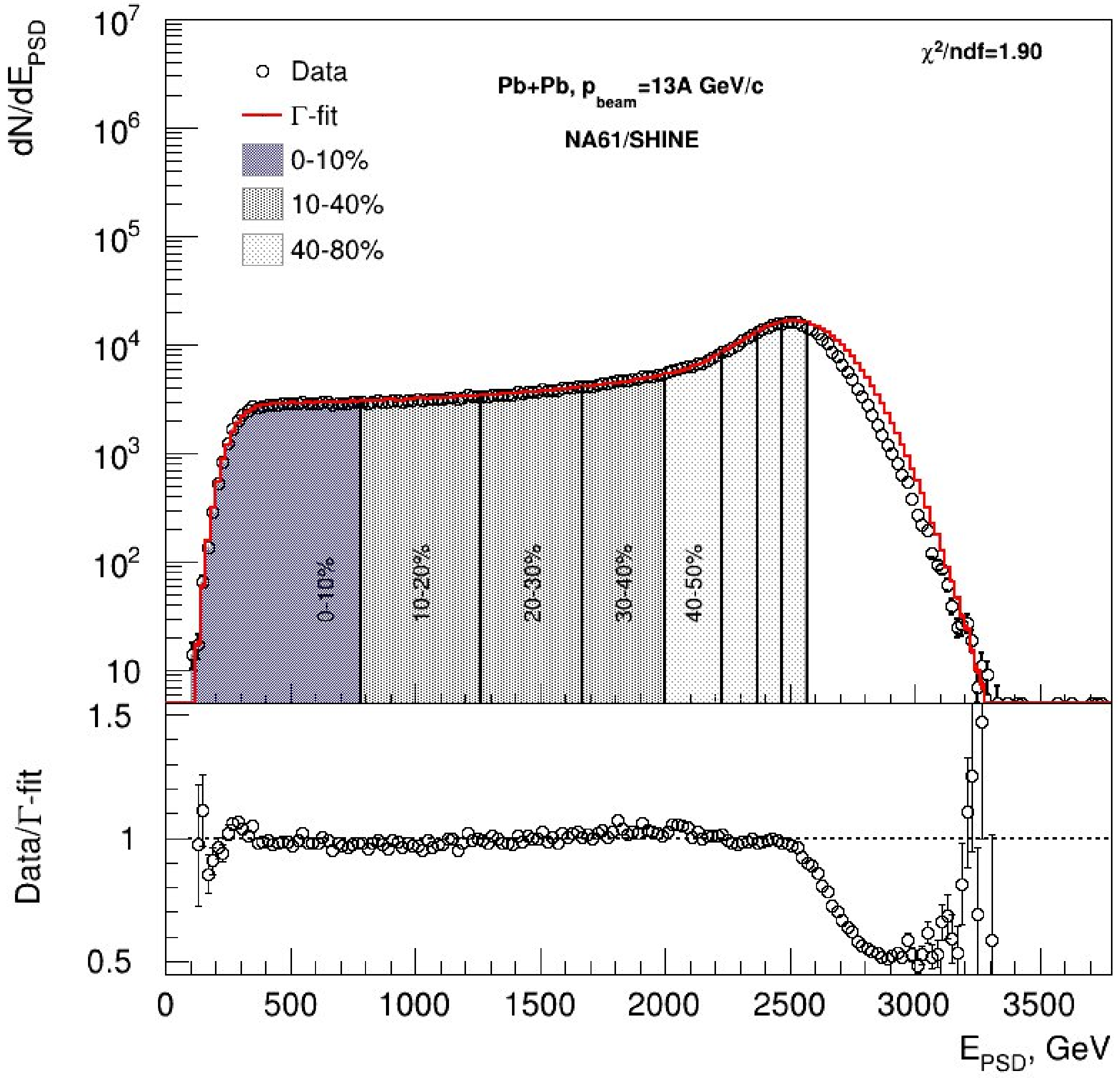
↓

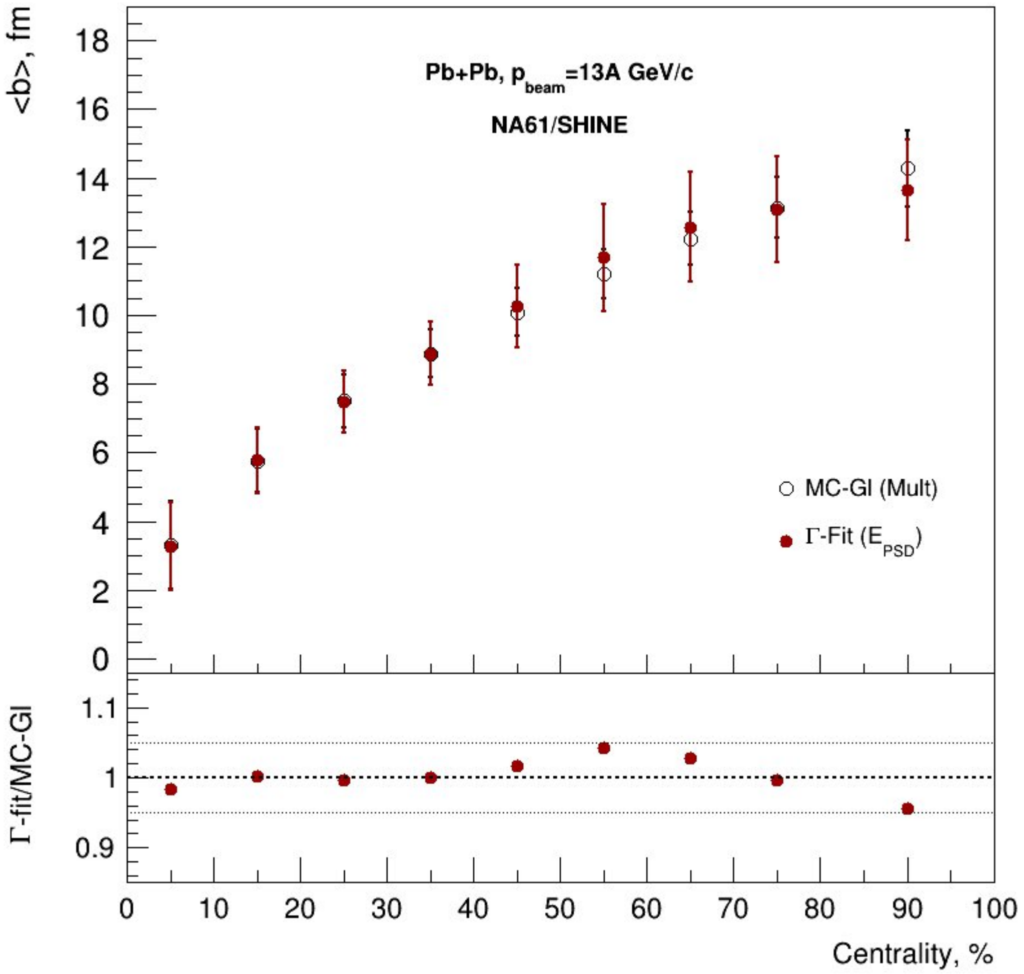
Construct P(b|E) using Bayes' theorem:
P(b|E) = P(b)P(E|b)/P(E)

For more details see D.Idrisov's talk on Cross-PWG 19.09.2023

Comparison with MC-Glauber fit

For more details see D.Idrisov's talk on Cross-PWG 19.09.2023





Good agreement between fit and data.

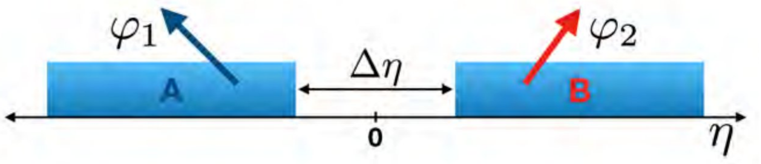
There is agreement within 5%.

Methods for v_n measurements

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

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

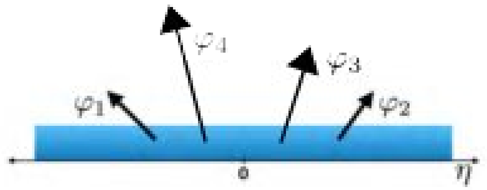
$$Q_n = \sum_{i=1}^{M} e^{in\phi} \qquad \langle 2 \rangle_{a|b} = \frac{Q_{n_a} Q_{n,b}^*}{M_a M_b} \qquad v_2\{2\} = \sqrt{\langle\langle 2 \rangle\rangle_{a|b}}$$



- **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

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

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

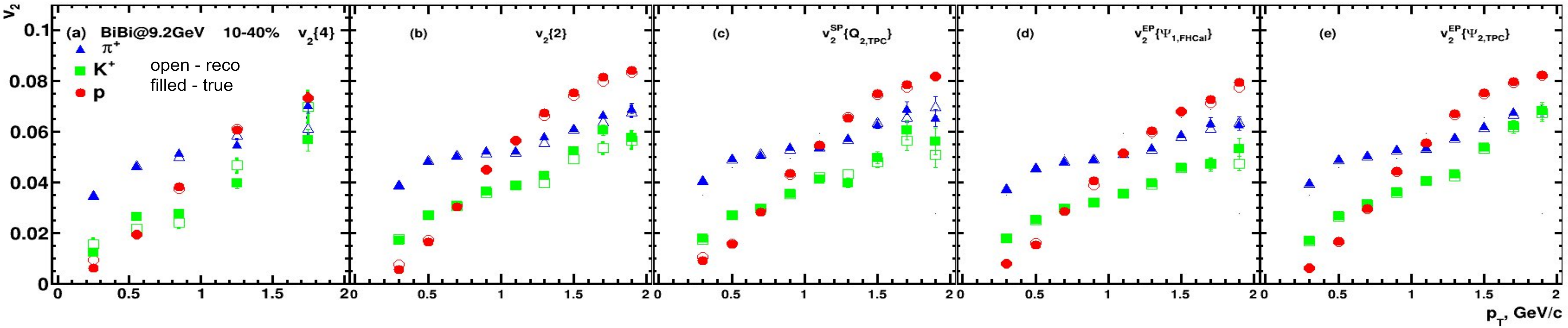
Here: ω_i - $p_{T,i}$ transverse momentum of the i-th track in the TPC

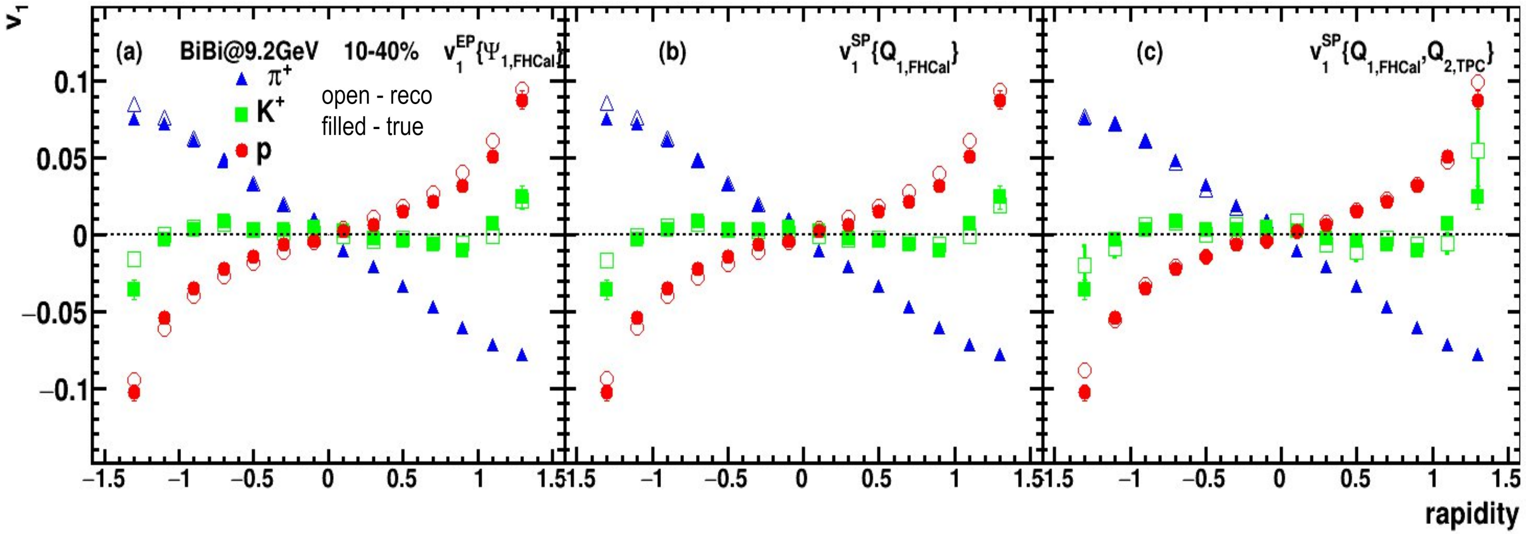
φ_i - azimuthal angle of the i-th track in the TPC

Ψ_n- event plane angles

Method's details described in PRC 83 (2011), 044913 , EP method: Phys.Rev.C 77 (2008) 034904

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



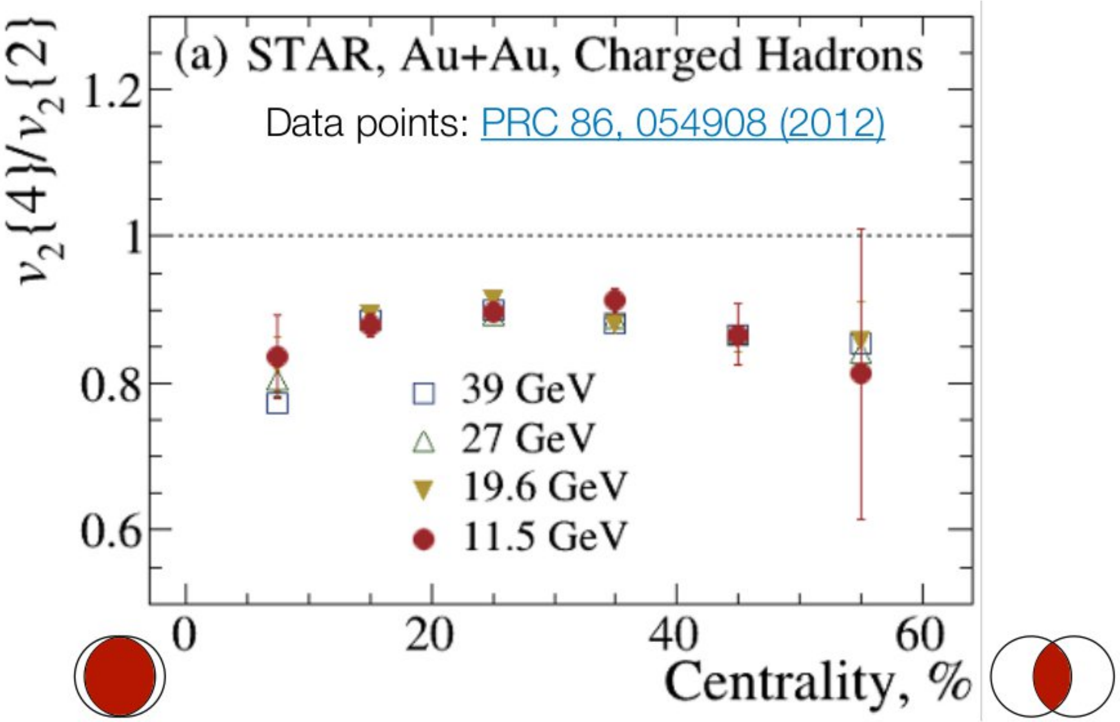


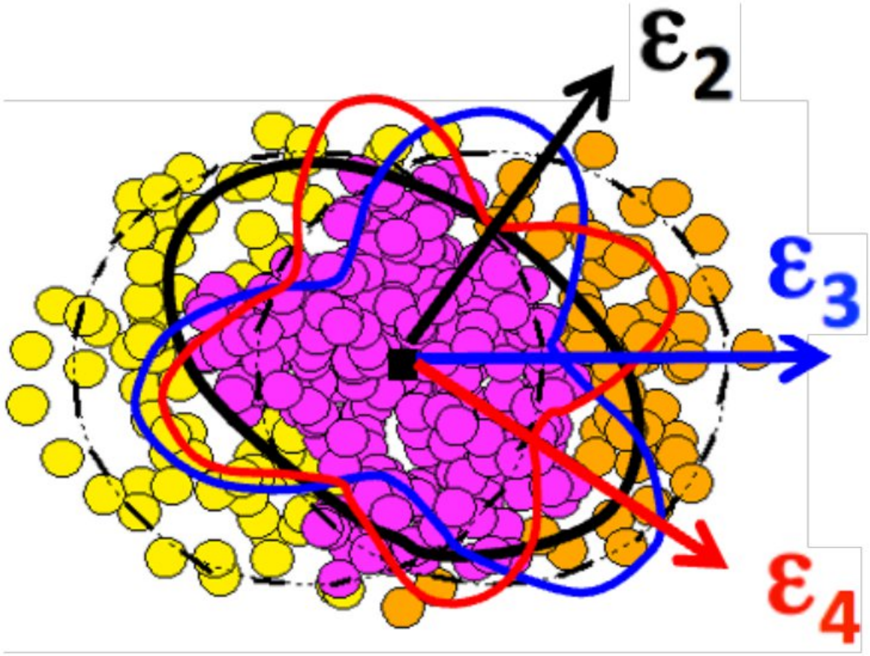
Gereal purpose production 25 was used

Good performance for v_1, v_2 using several methods for flow measurements (EP, SP, Q-Cumulants)

Good performance for flow measurements for all methods used (EP, SP, Q-cumulants)

Motivation of elliptic flow fluctuation study





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

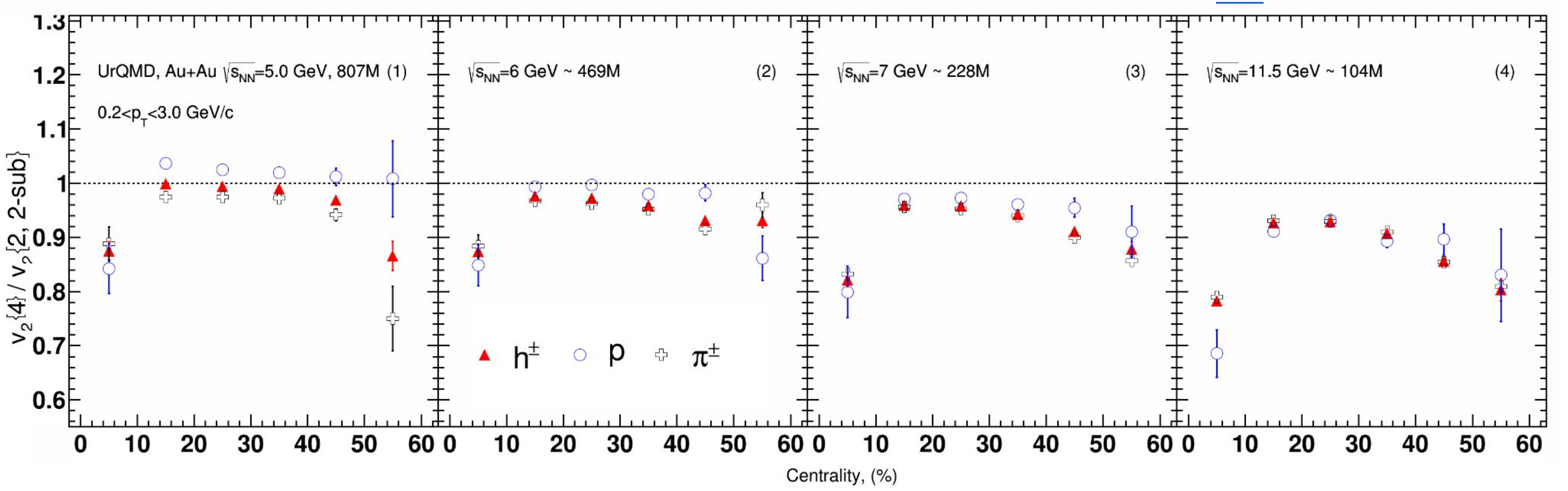
- Weak dependence on collision energy

- Indicate a dominated initial state driven uctuations $\sigma_{\varepsilon 2}$
- Provide constraints for IS models and shear viscosity η(T/s)

How about v_2 fluctuations at NICA energies?

Relative v_2 fluctuations of identified hadrons

For more details see A.Demanov's talk on ISHEP-2023



- Weak dependence between $v_2\{4\}/v_2\{2\}$ of protons and pions at 11.5 GeV
- The difference between $v_2\{4\}/v_2\{2\}$ of protons and pions increases with decreasing energy

Event plane Resolution

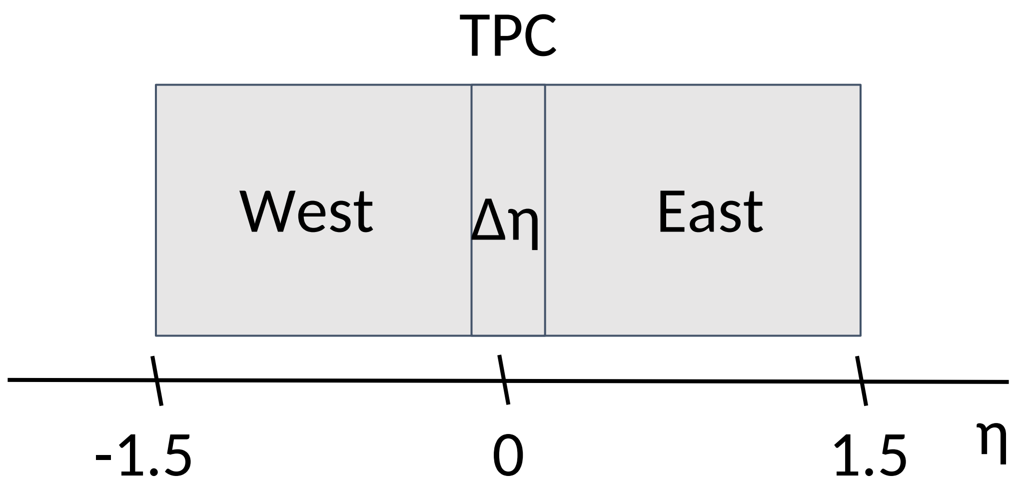
in vHLLE+UrQMD Bi+Bi $\sqrt{s_{NN}}$ = 9.2 GeV

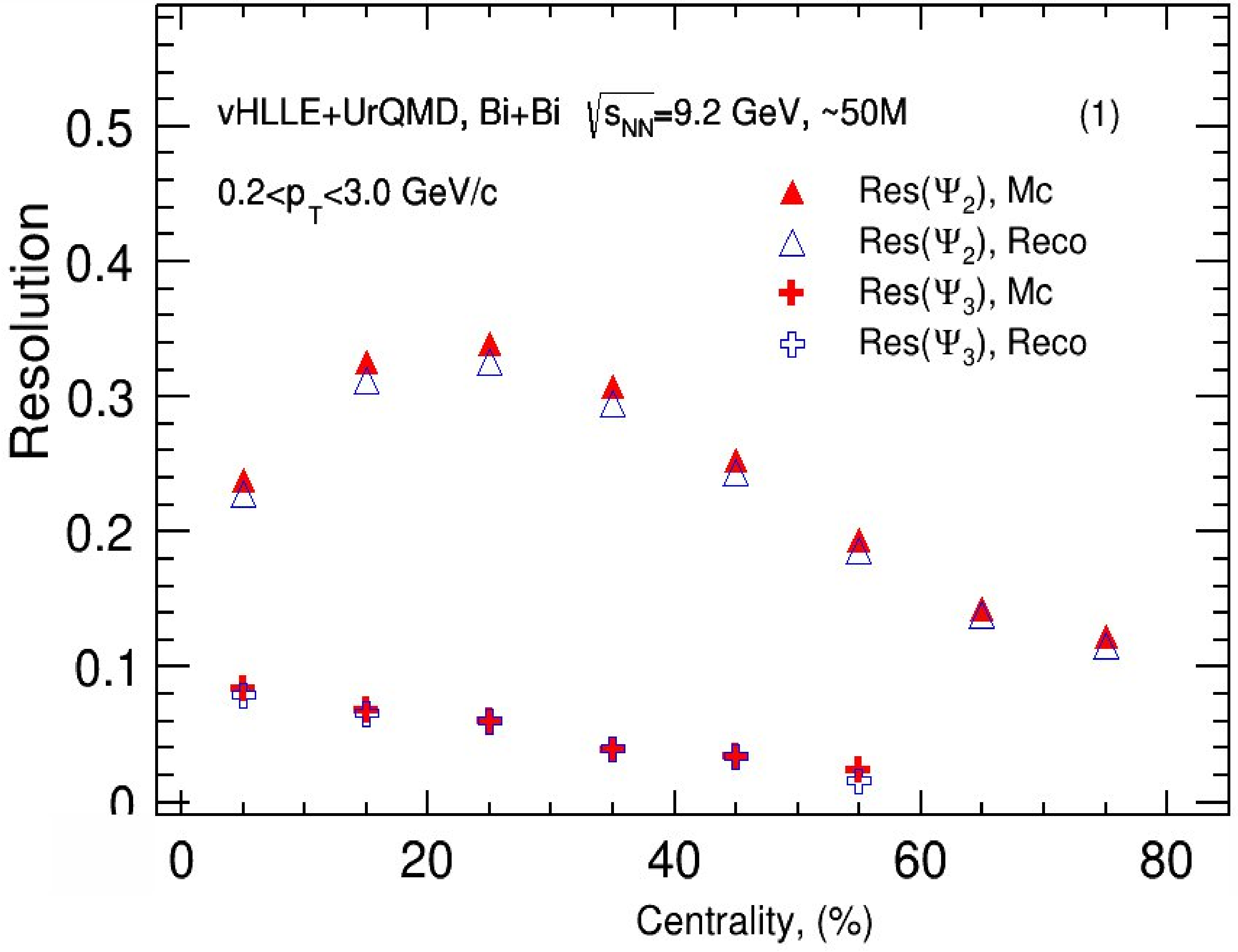
2 sub event: Δη=0.1

$$Res\{\Psi_n^{E(W)}\} = \sqrt{\langle \cos\left[n(\Psi_n^E - \Psi_n^W)\right]\rangle}$$

Anisotropic flow is measured as follows:

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

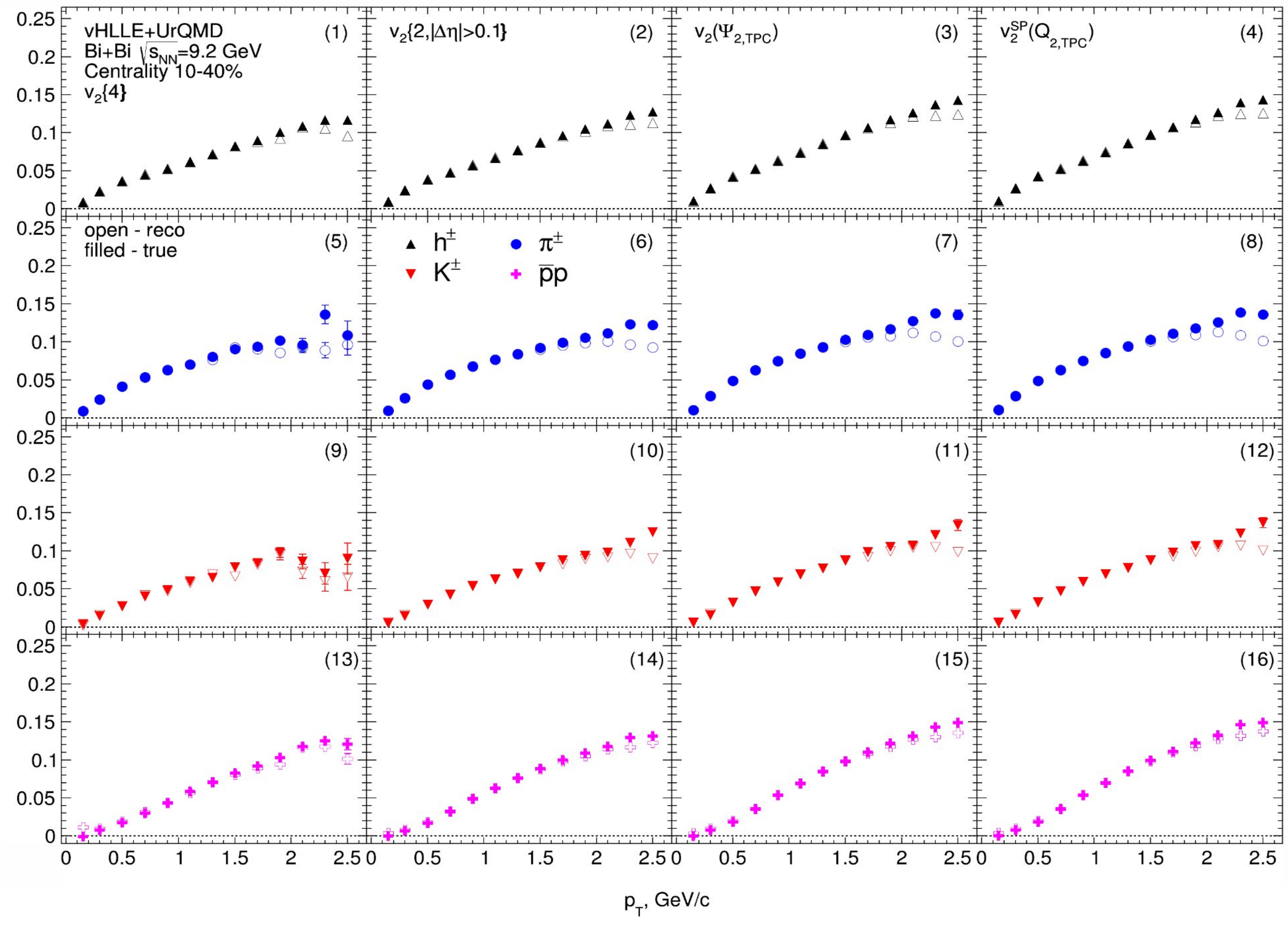




Mass production 32 was used

- We do not measure the Ψ_3 resolution after to 60% centrality
- Ψ_3 resolution are smaller than Ψ_2
- Good agreement between $R_{MC}(\Psi_n)$ and $R_{reco}(\Psi_n)$

Comparison of Reco and MC: v_2 eta-sub EP

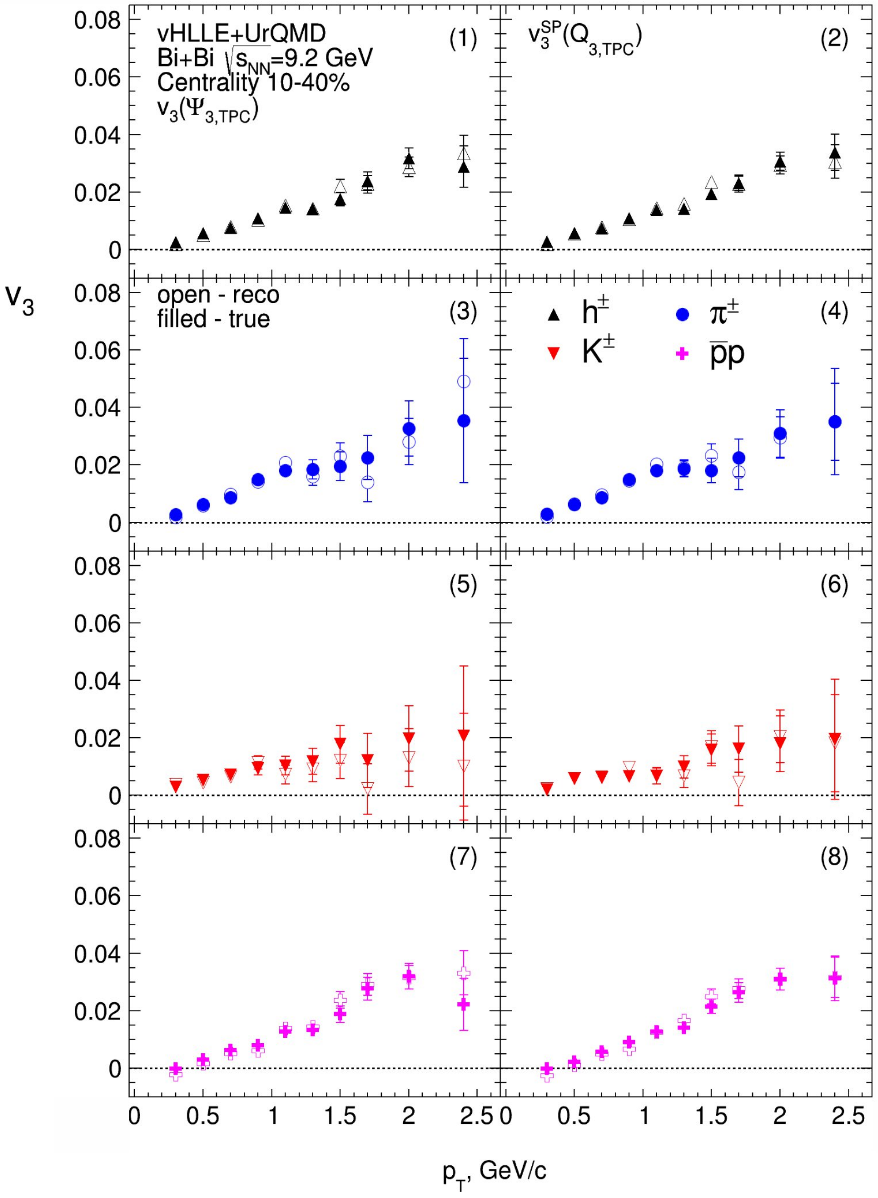


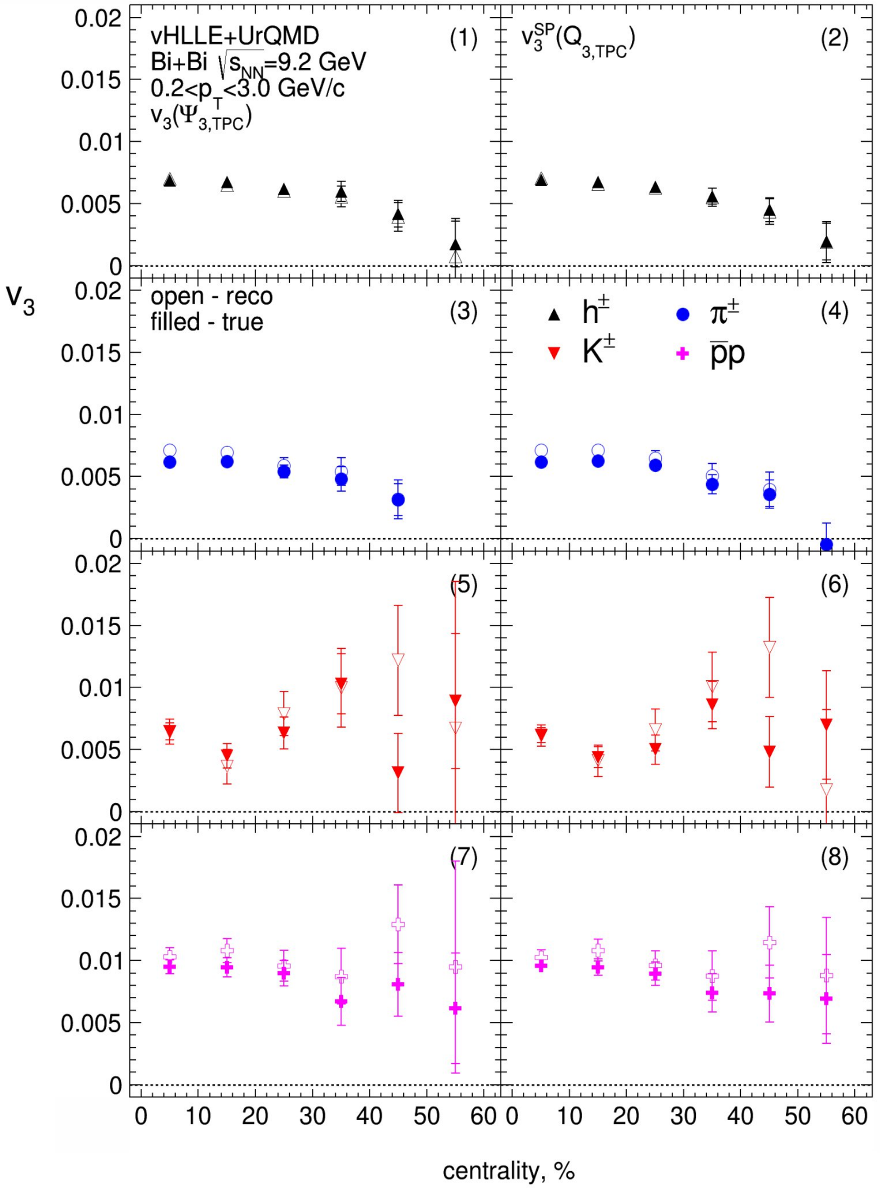
Cuts:

- Charged particles only
- Primary
- $|\eta|<1.5$
- $\Delta\ \eta$ = 0,1
- p_T >0.2 GeV/c
- $|DCA|<3\sigma$
- nTPC hits ≥ 16
- PID: PDG code

- ❑ good agreement of the $v_{2,mc}$ with $v_{2,reco}$ data
- ❑ The difference at highp_T between $v_{2,mc}$ and $v_{2,reco}$ (non-flow)

Comparison of Reco and MC: v_3 eta-sub EP





Cuts:

- Charged particles only
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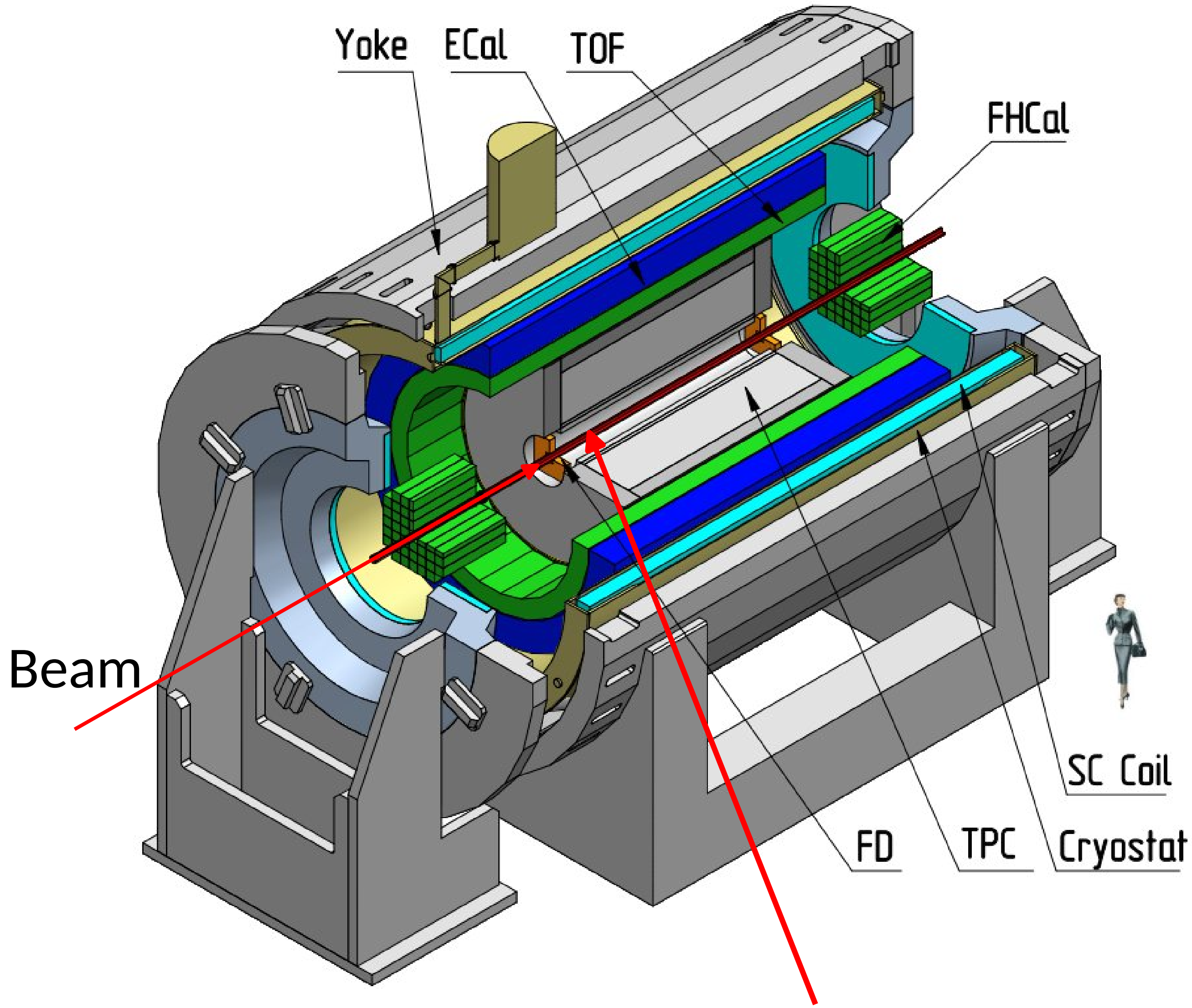
- $|\eta|<1.5$
- $\Delta\ \eta = 0{,}1$
- p_T >0.2 GeV/c
- $|DCA|<3\sigma$
- nTPC hits ≥ 16
- PID: PDG code

- ❑ Good performance for v_3 measurements
- ❑ More statistics needed for more precise v_3 measurements

MPD in Fixed-Target Mode (FXT)



Target (z=-115 cm)

Mass production 33 was used

- Model used: UrQMD mean-field
  - Bi+Bi, E_{kin}=1.45 AGeV ($\sqrt{s_{NN}}$=2.5 GeV)
  - Bi+Bi, E_{kin}=2.92 AGeV ($\sqrt{s_{NN}}$=3.0 GeV)
  - Bi+Bi, E_{kin}=4.65 AGeV ($\sqrt{s_{NN}}$=3.5 GeV)
- Point-like target
- GEANT4 transport
- Particle species selection via true-PDG code of the associated MC particle

Flow vectors

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

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

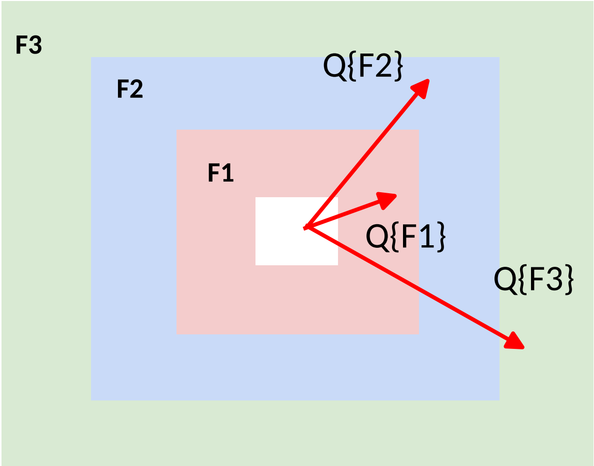
where φ is the azimuthal angle

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

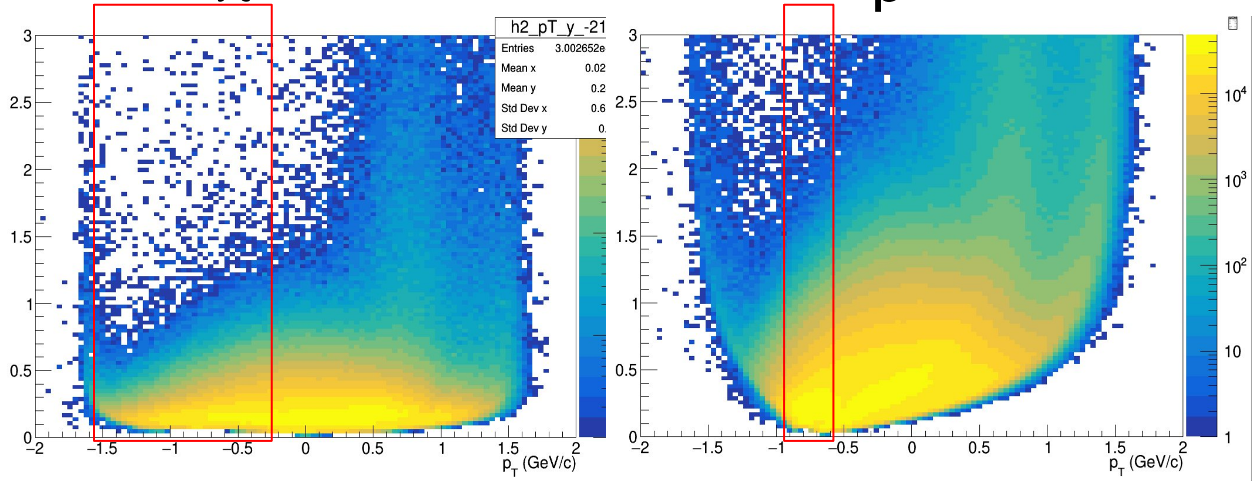
$$Q_n = \frac{\sum_{k=1}^{N} w_n^k u_n^k}{\sum_{k=1}^{N} w_n^k} = |Q_n| e^{in\Psi_n^{EP}}$$

Ψ_n^{EP} is the event plane angle

Modules of FHCal divided into 3 groups



π- p

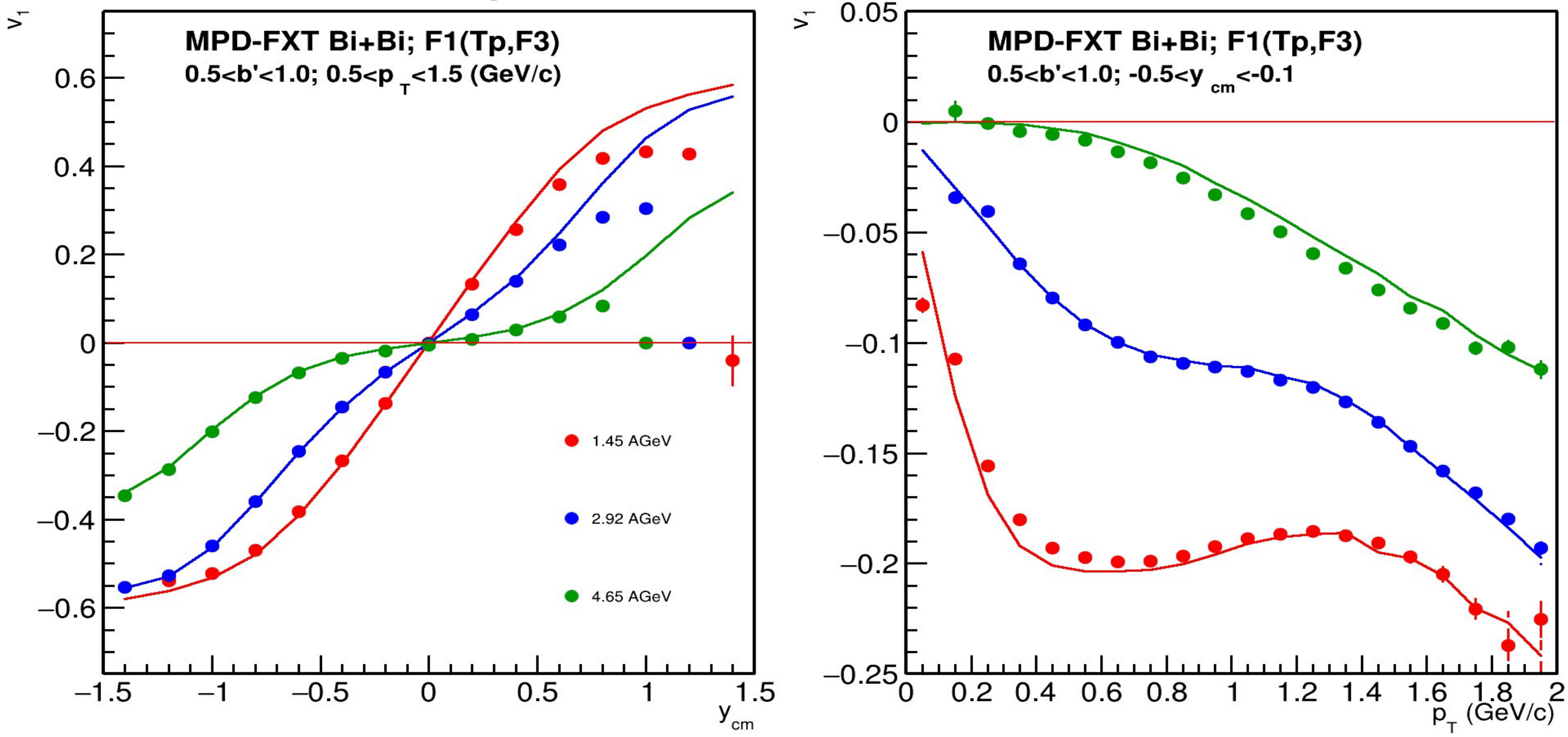


Additional subevents from tracks not pointing at FHCal:

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

Tπ: π-; -1.5<y<-0.2;

MPD-FXT: v_1 for protons

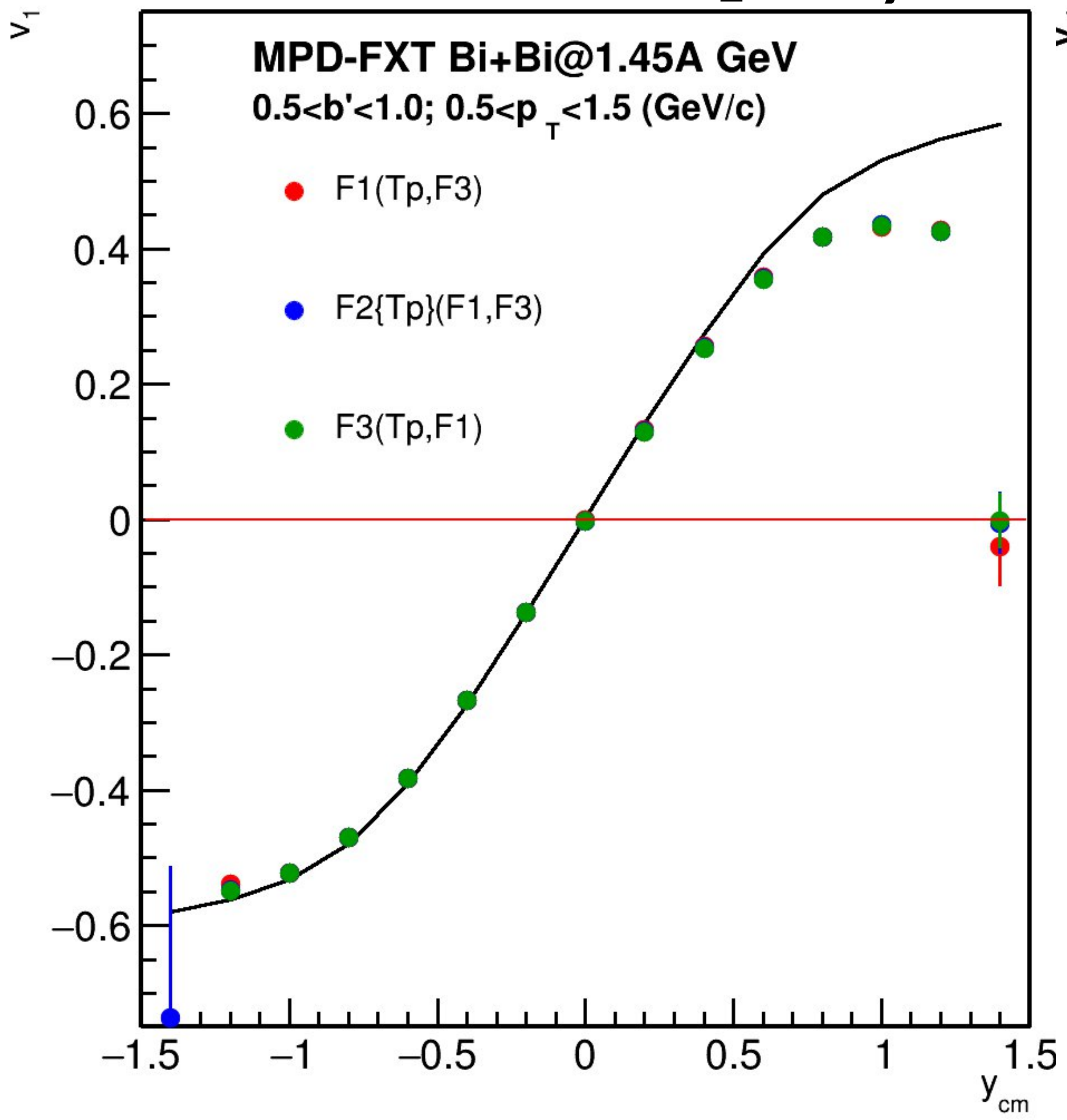


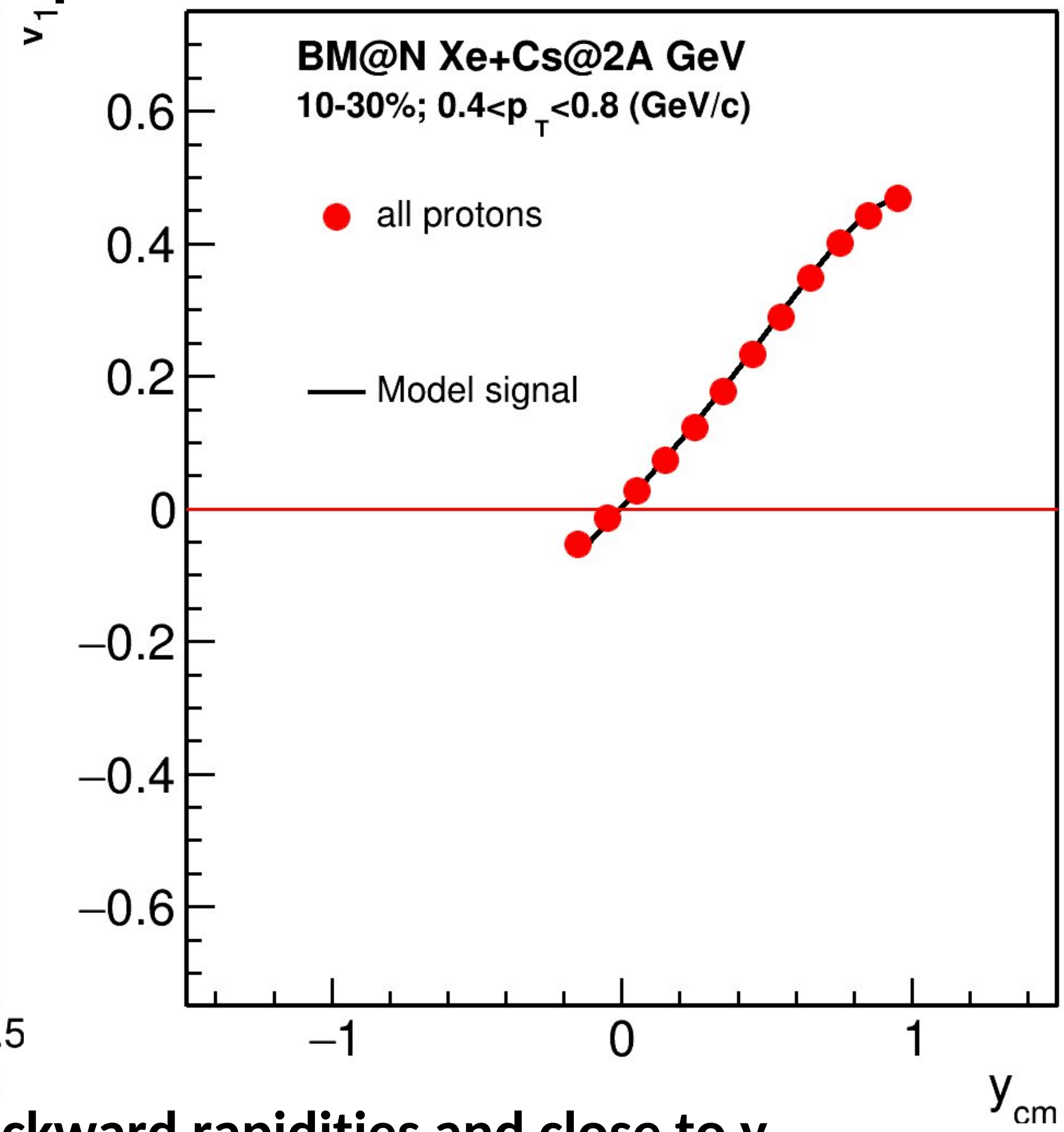
v_1 is consistent with model signal for y < 0.5

No efficiency corrections were applied yet

BM@N vs MPD: v_1 vs y for protons

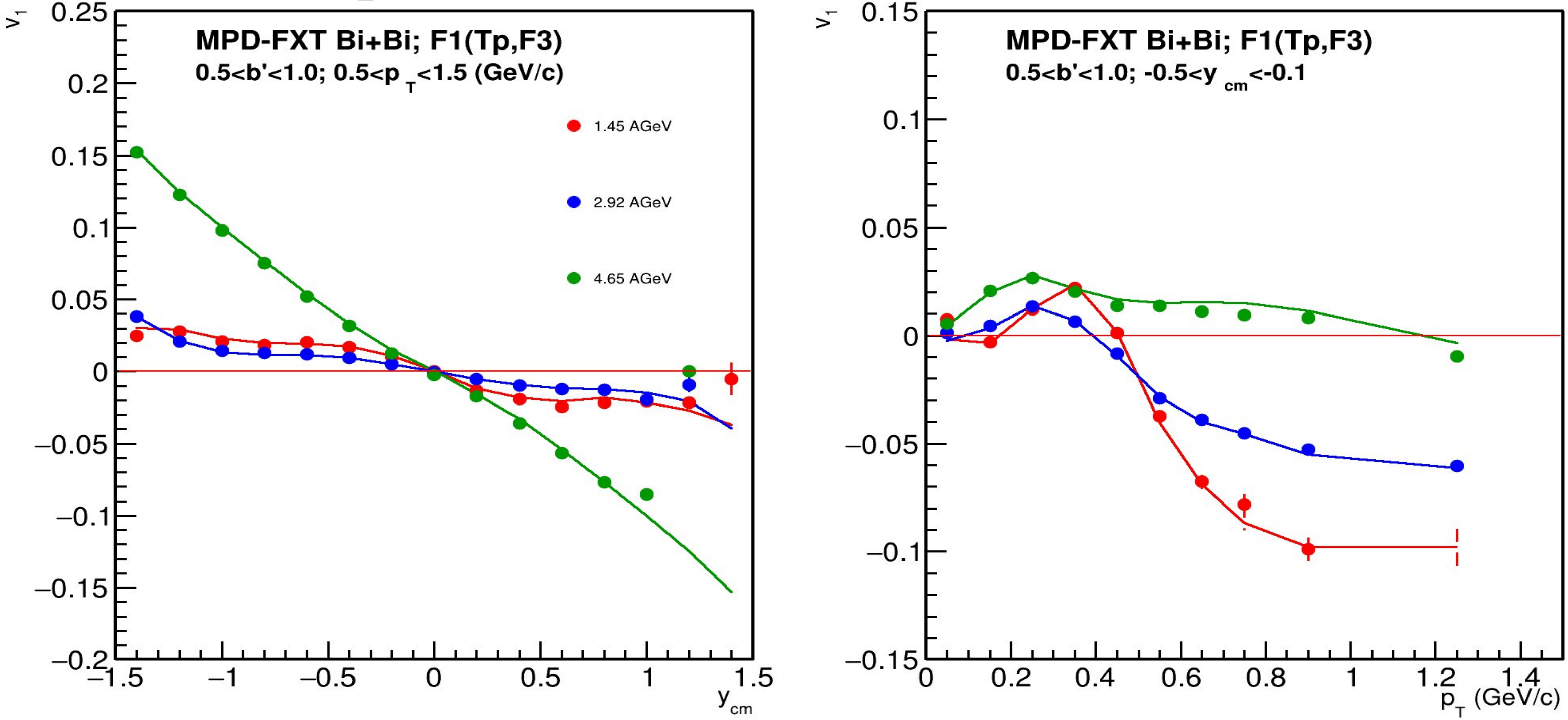
See M.Mamaev's talk at ISHEP-2023 and at Cross-PWG 5.09.2023





MPD has better coverage in backward rapidities and close to y_{beam}

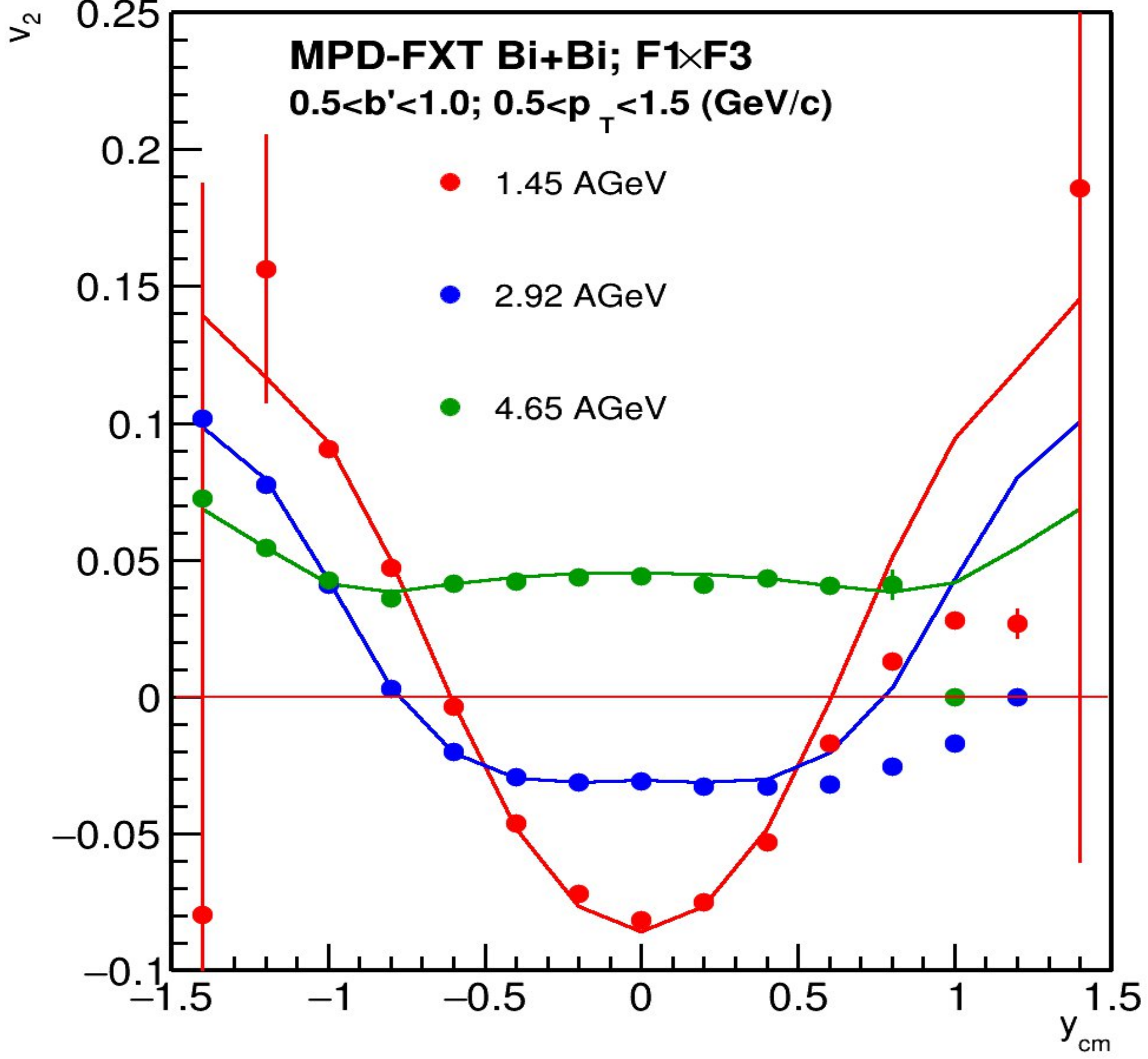
MPD-FXT: v_1 for π^-

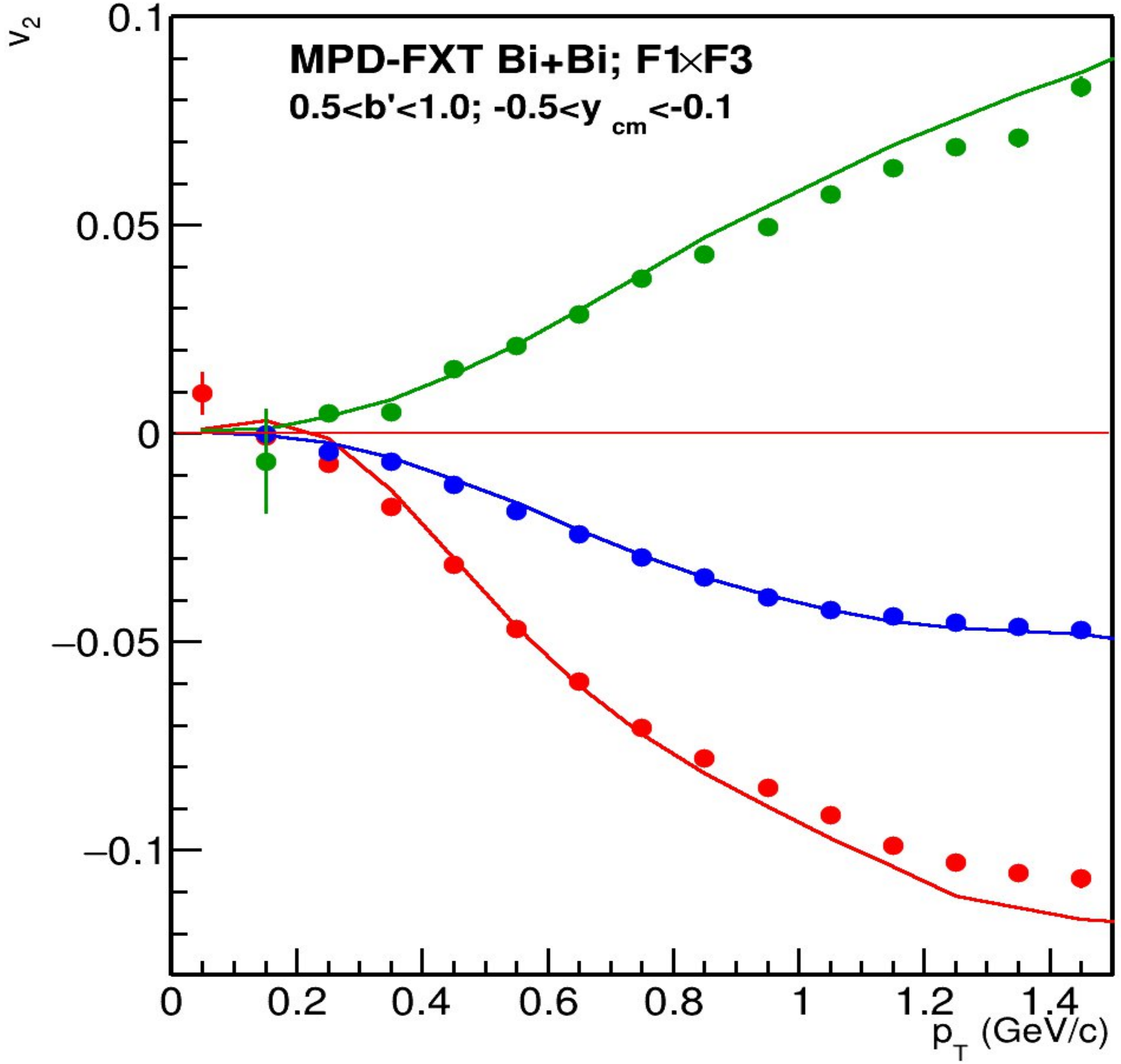


v_1 is consistent with model signal for y < 1

No efficiency corrections were applied yet

MPD-FXT: v_2 for protons



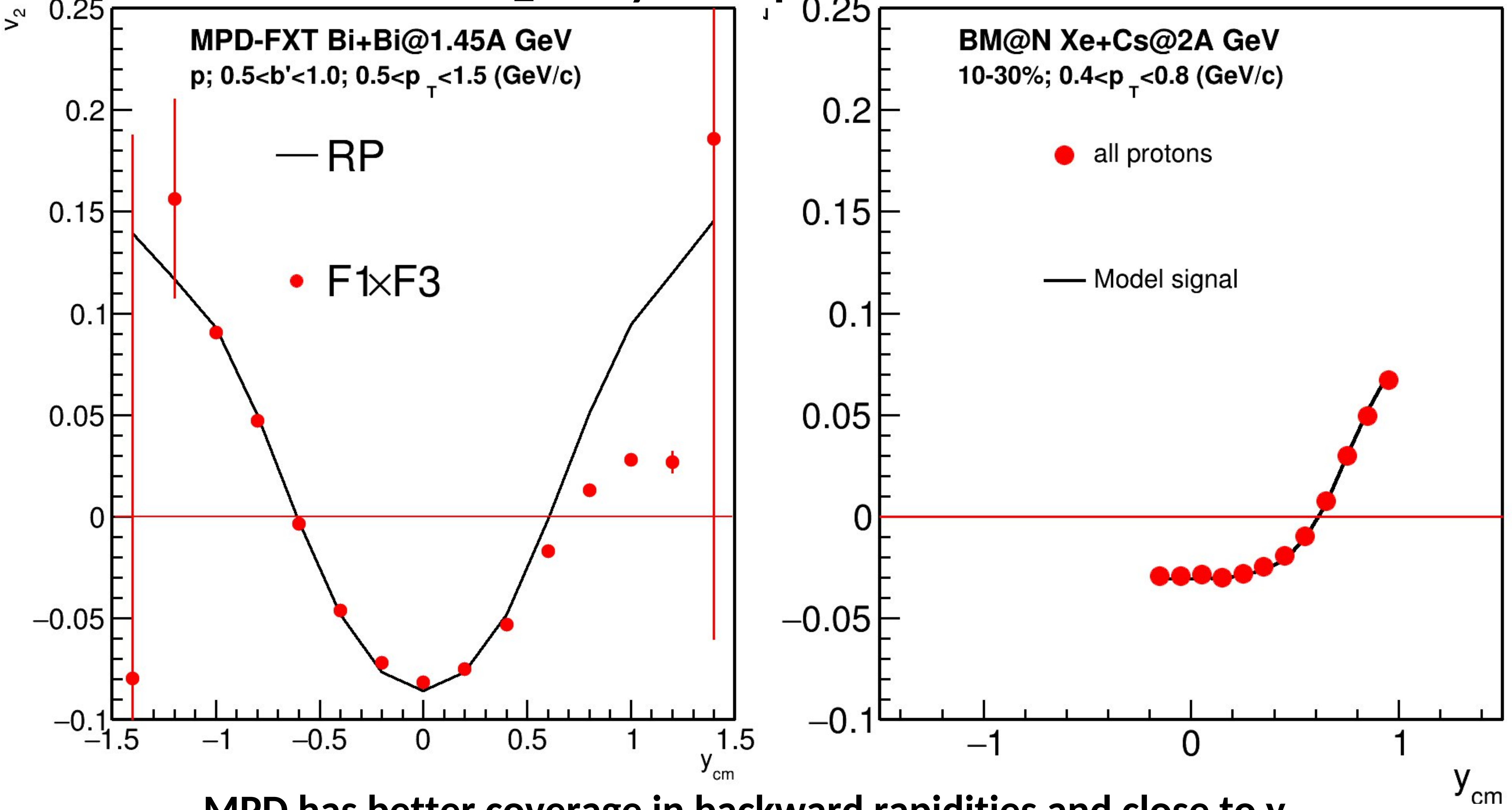


v_2 is consistent with model signal for y < 0.5

No efficiency corrections were applied yet

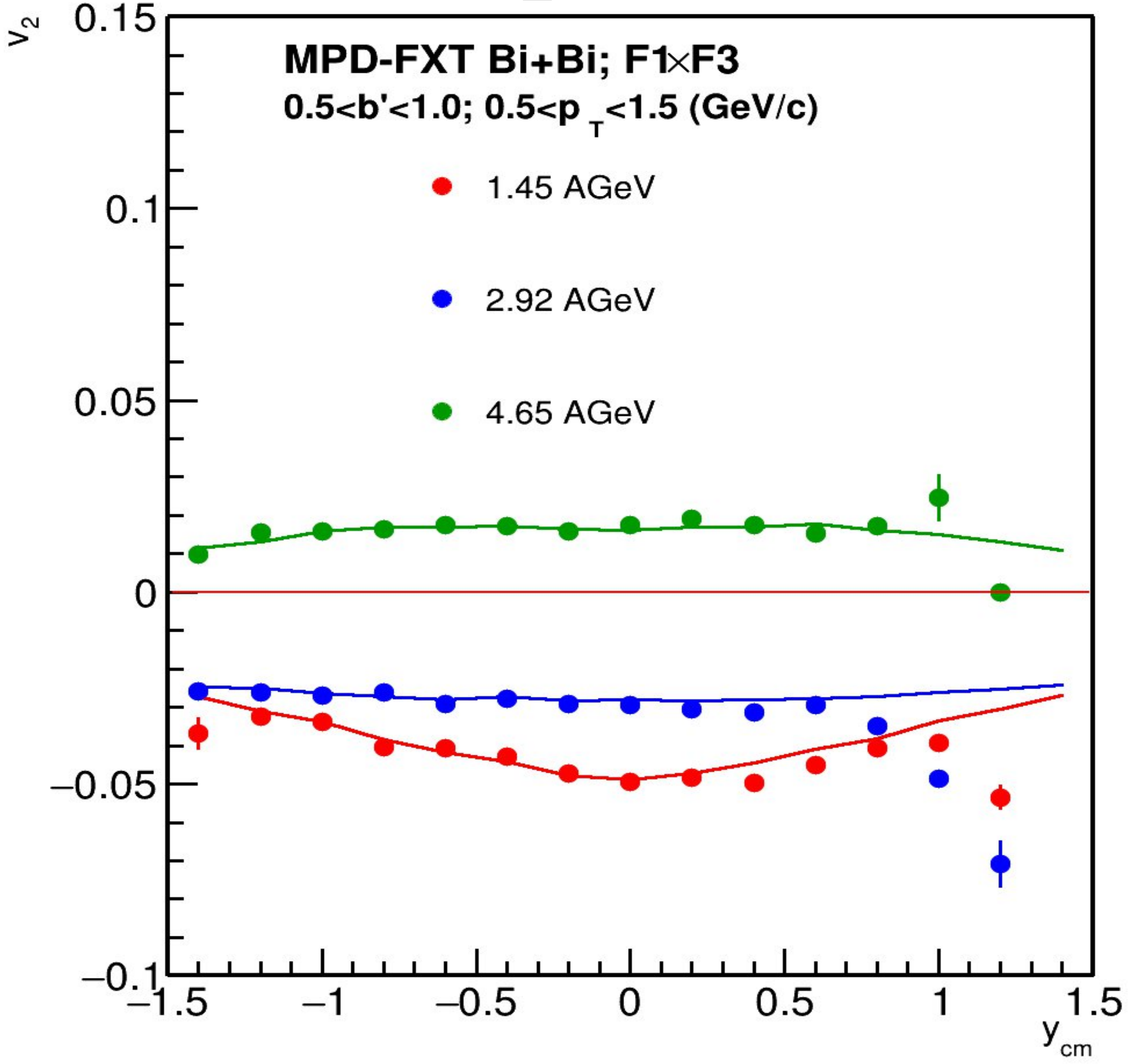
BM@N vs MPD: v_2 vs y for protons

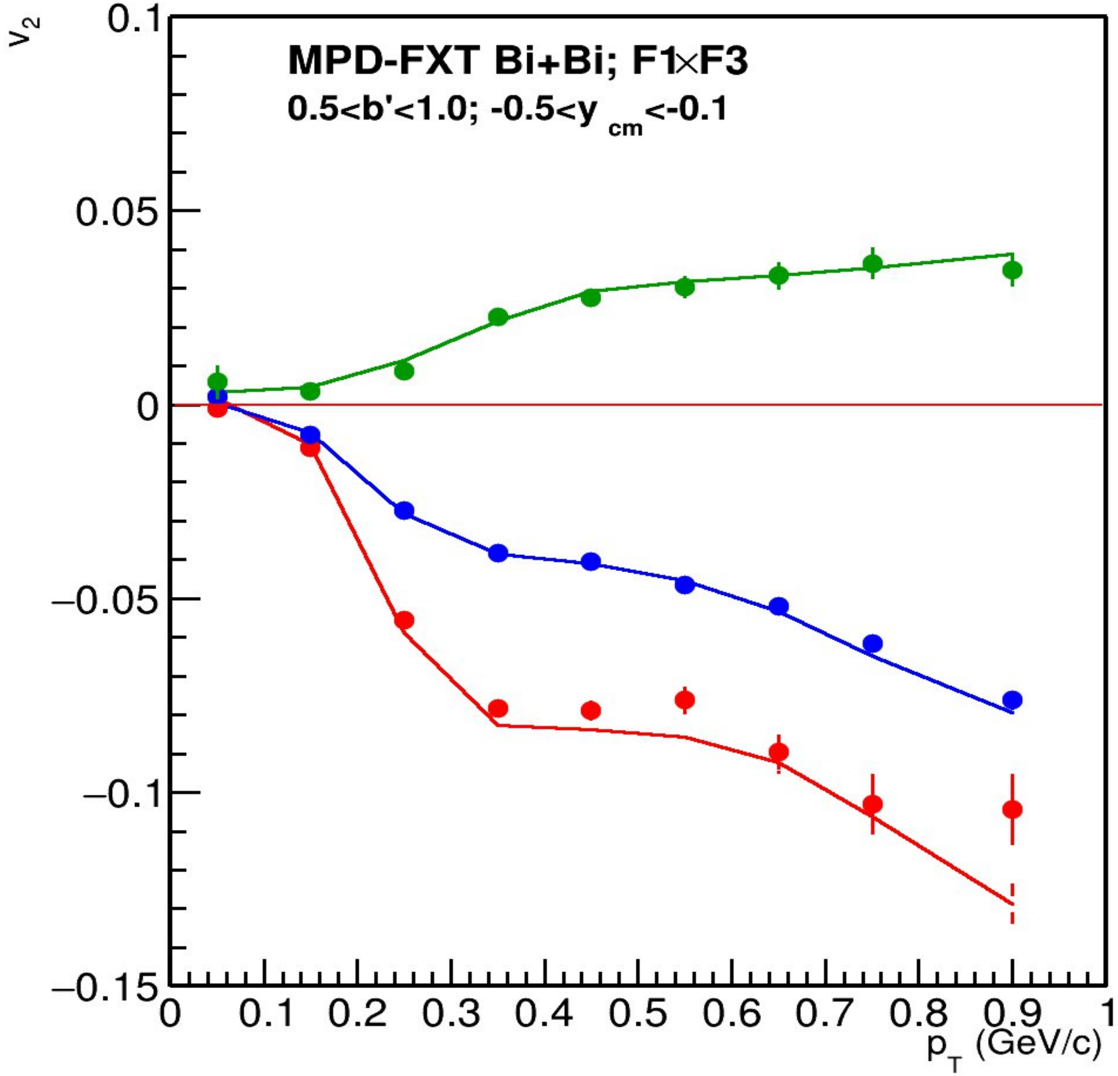
See M.Mamaev's talk at ISHEP-2023
and at Cross-PWG 5.09.2023



MPD has better coverage in backward rapidities and close to y_{beam}

MPD-FXT: v_2 for π^-





v_2 is consistent with model signal for y ≲ 0.5

No efficiency corrections were applied yet

Summary and Outlook

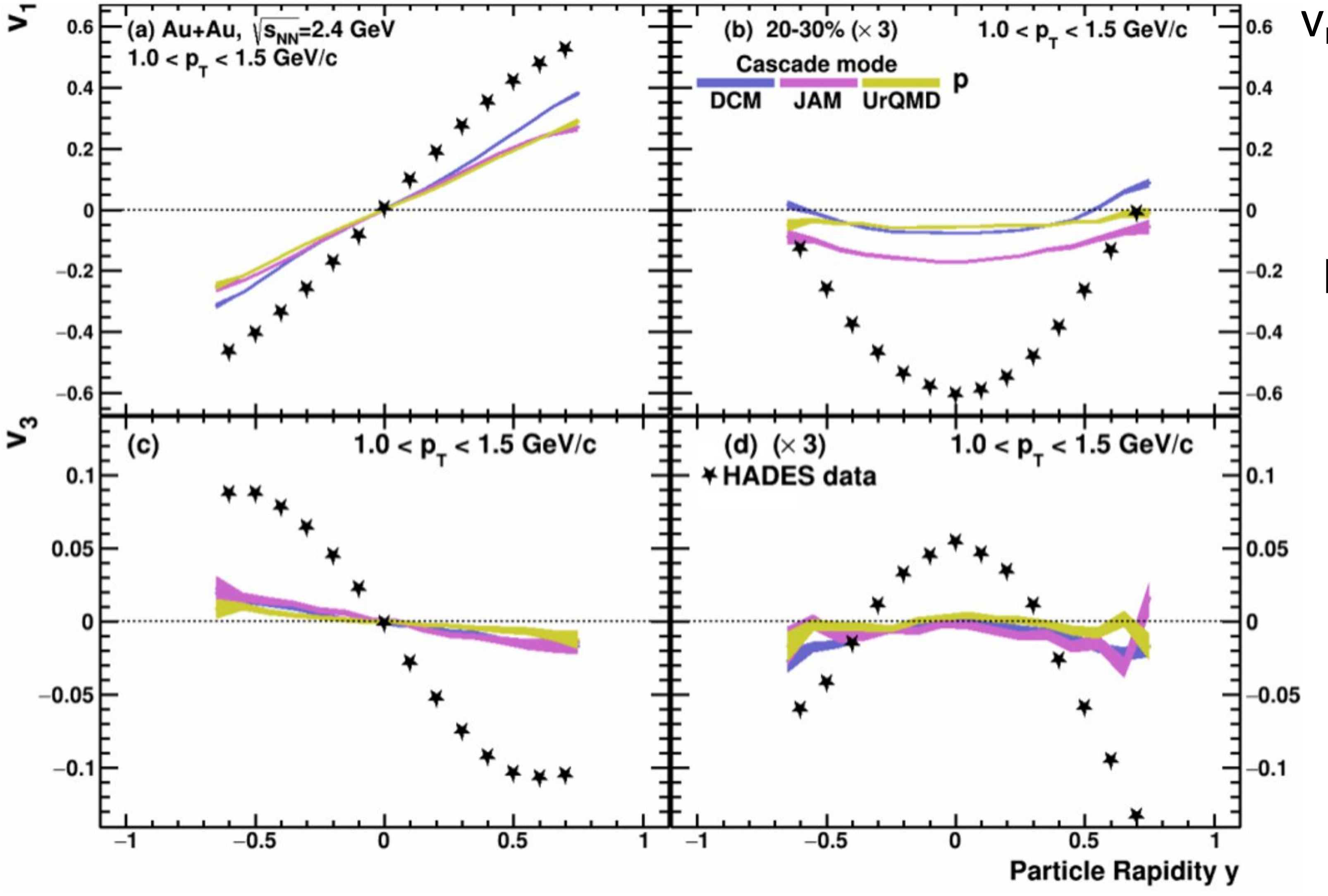
- **Centrality determination procedures in MPD:**
  - Centrality determination using spectator energy is being developed using both MC-Glauber and inverse Bayes approaches
  - Further improvements are in progress
- **Relative elliptic flow fluctuations at lower NICA energies is being studied:**
  - PID dependence of $v_2\{4\}\ /v_2\{2\}$ is observed at energy $\sqrt{s_{NN}}$ = 5 GeV
  - More statistics needed to make multi-differential study of $v_2\{4\}\ /v_2\{2\}$ of identified charged hadrons
- **Feasibility study for anisotropic flow:**
  - evPlane wagon for event plane measurements was implemented in the MpdRoot, wagon for the flow measurements will be added soon
  - Results from reconstructed and generated data are in a good agreement for all methods for UrQMD (req. 25) and vHLLE+UrQMD (req. 32) models
  - First results on flow performance for MPD in fixed-target mode: good agreement between reconstructed and generated data in backward rapidity and midrapidity regions

Thank you for your attention!

Backup slides

Selecting the model

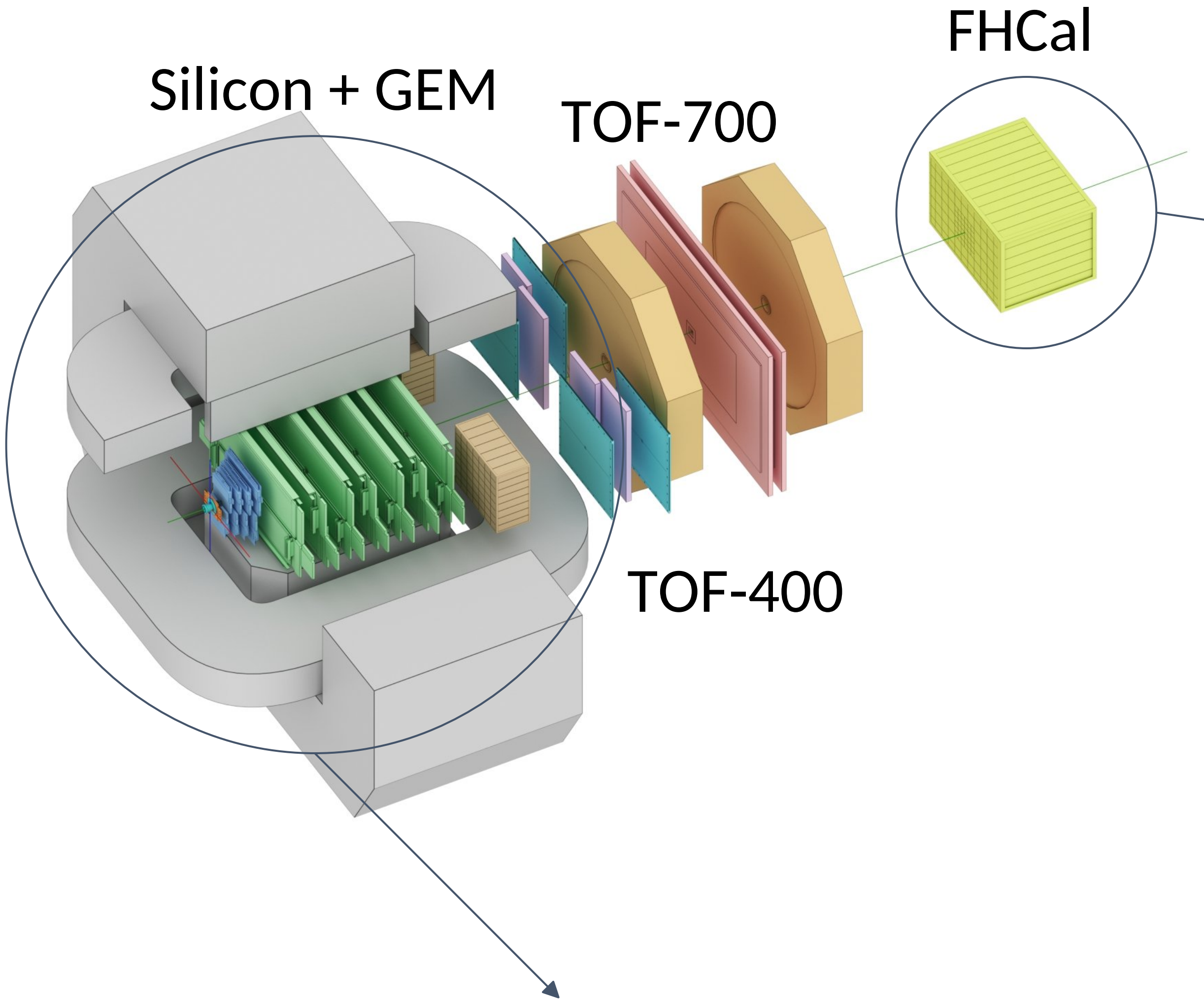
P.Parfenov Particles 5 (2022) 4, 561-579

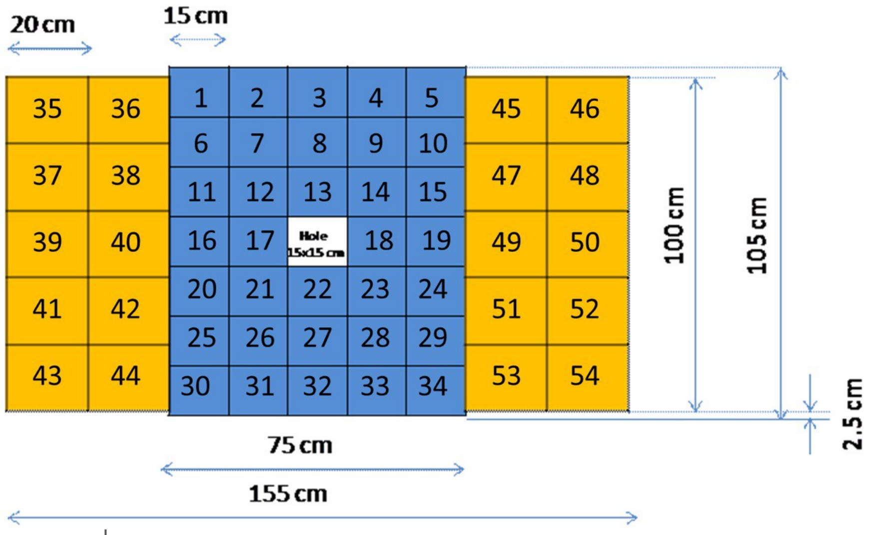


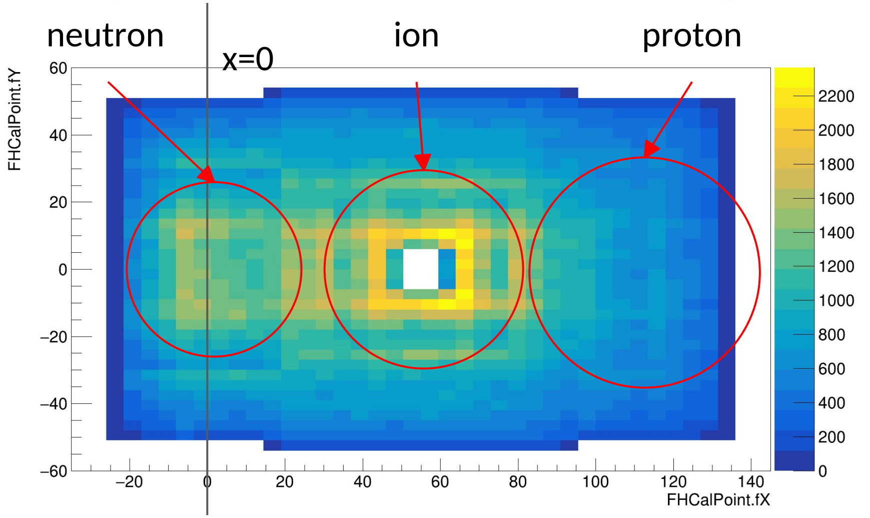
Cascade models fail to reproduce v_n at low-energy heavy-ion collision

Mean field models reproduce the v_n rather well

The BM@N experiment (GEANT4 simulation for RUN8)



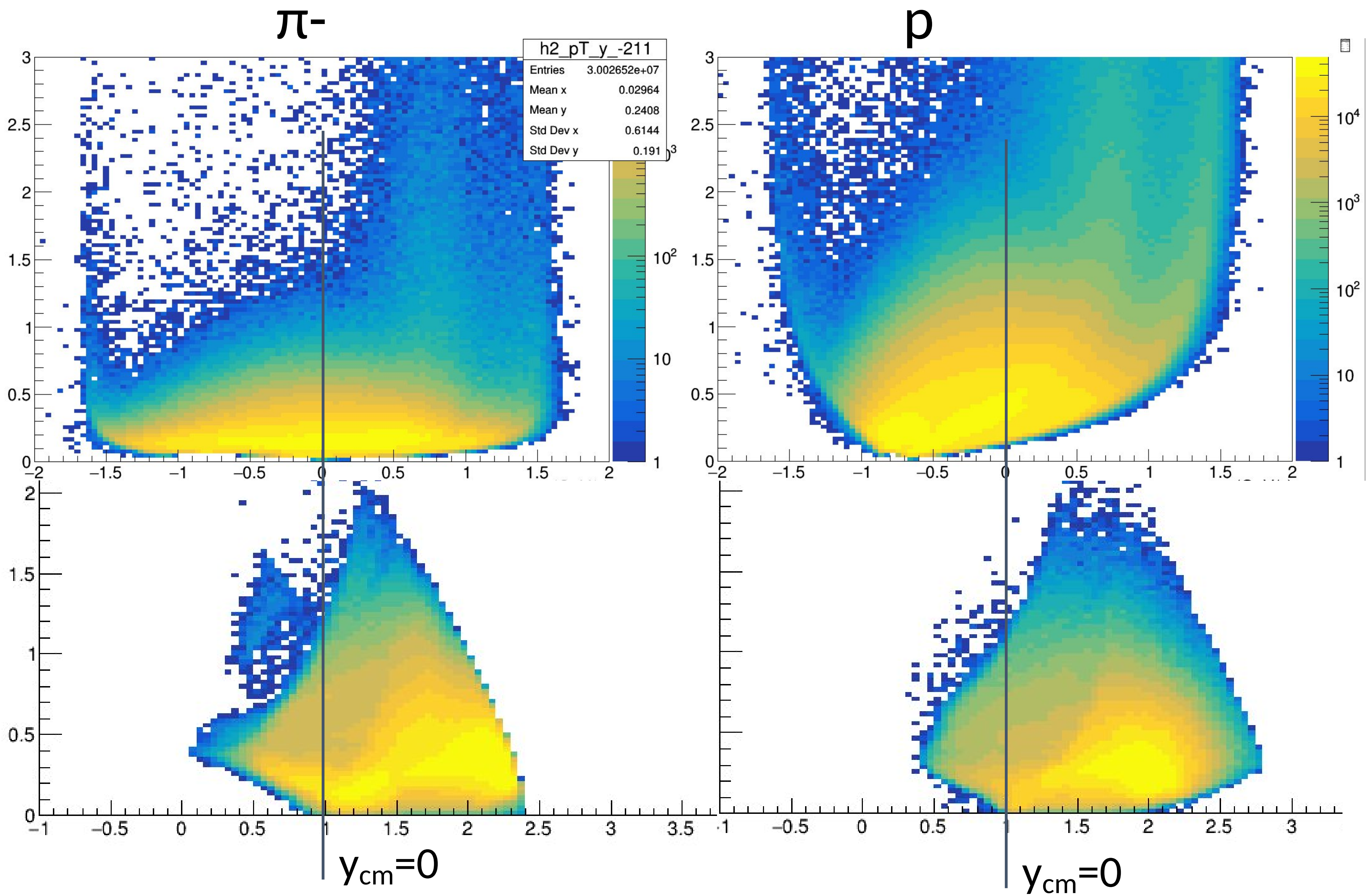




Square-like tracking system within the magnetic field deflecting particles along X-axis

Charge splitting on the surface of the FHCal is observed due to magnetic field

BM@N vs MPD: p_T-y acceptance

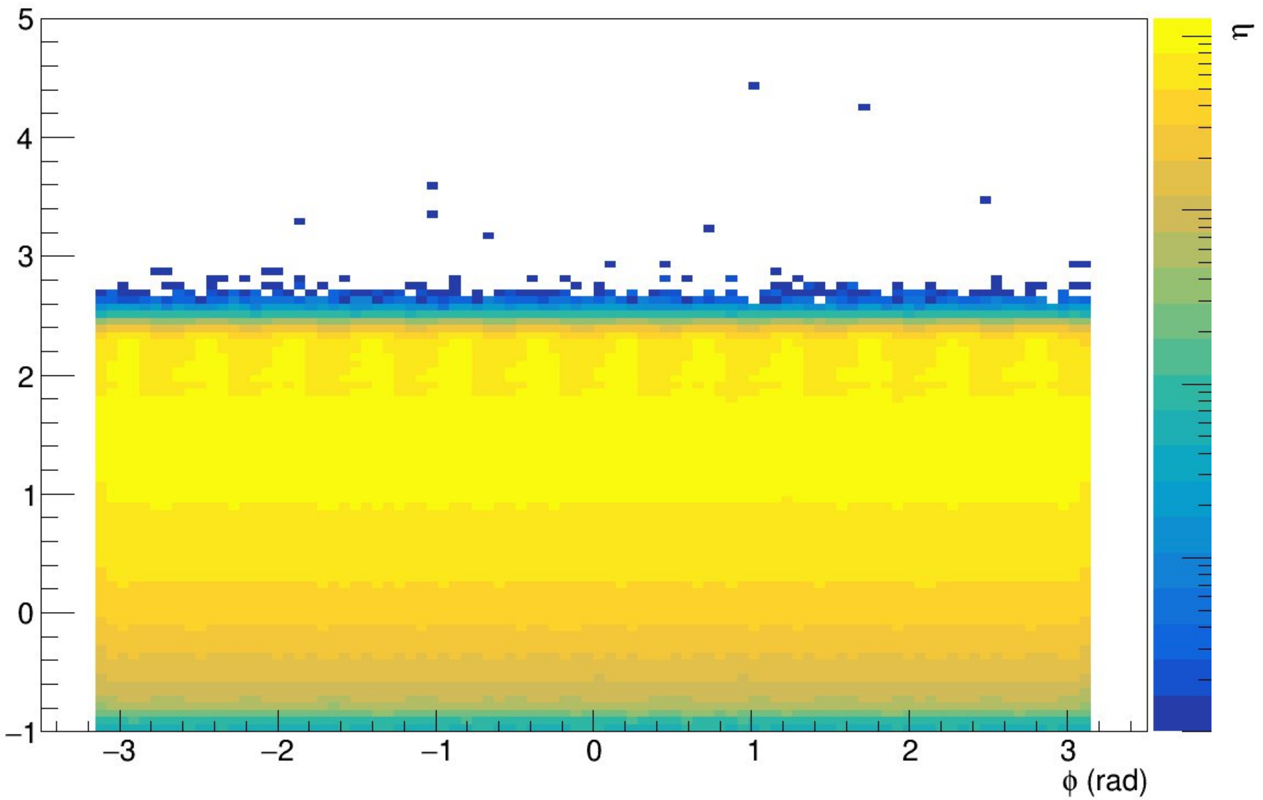


MPD has greater coverage of backward area (even covers projectile spectators) and MPD covers midrapidity region

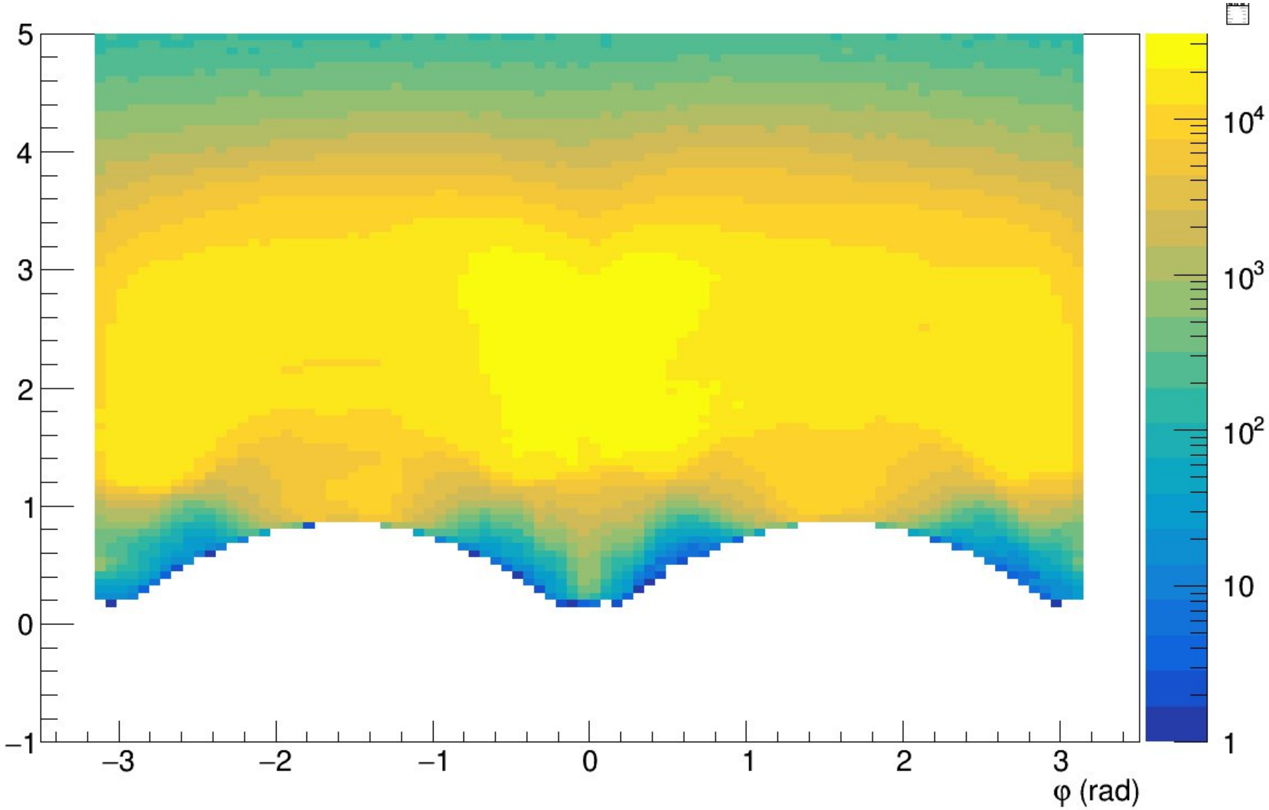
BM@N has greater coverage of forward area

BM@N vs MPD: η-φ acceptance

MPD

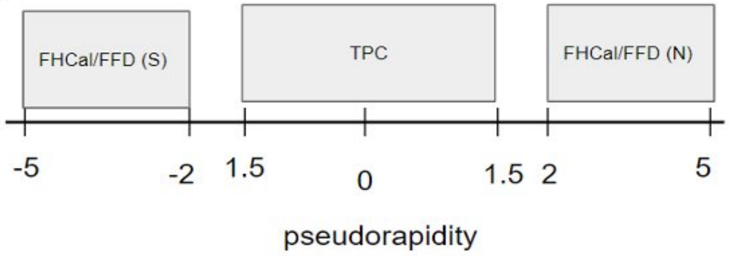


BM@N



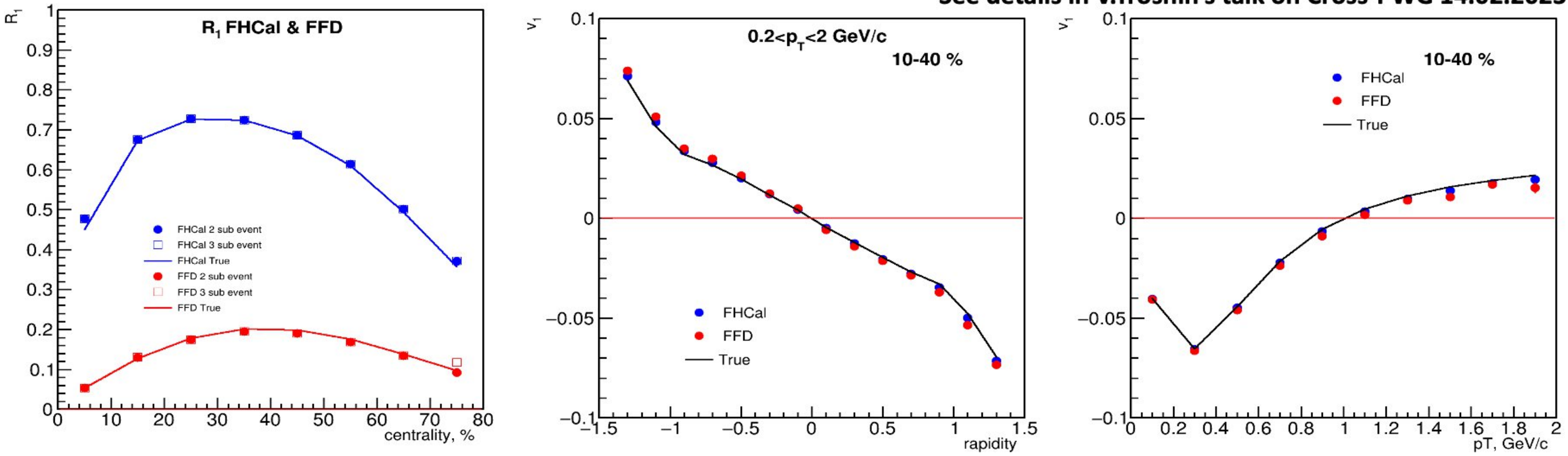
- MPD has more uniform acceptance along φ-axis
- BM@N has non-uniform acceptance due to square-like shape of the tracking system

FHCal and FFD comparison for v_n in MPD



true	2 sub events	3 sub events
$R_{1,i}^{True} = \langle Q_{1,i}\Psi_{RP}\rangle$	$R_{1,i} = \sqrt{\langle Q_{1,i}^{N} Q_{1,i}^{S}\rangle}, i = x, y$	$R_{1,i}^{N} = \sqrt{\frac{2\langle Q_{1,i}^{N} Q_{1,i}^{S}\rangle\langle Q_{1,i}^{S} Q_{1,i}^{TPC}\rangle}{\langle Q_{1,i}^{N} Q_{1,i}^{TPC}\rangle}}$

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

Summary for main topic 1

- Software implementation of MC Glauber and Γ-fit with multiplicity based fitting procedure is used for MPD
- Relation between impact parameter and centrality classes is extracted

- Centrality determination procedures based on MC sampling of spectators energy are developed
  and tested based on NA61/SHINE data for both MC-Glauber and inverse Bayes approaches
- Results are tuned on the spectator production implemented in the DCM-QGSM-SMM model
- Simplified procedure for hadron calorimeters based on Gauss distribution is also proposed for MC-Glauber approach

Work in progress

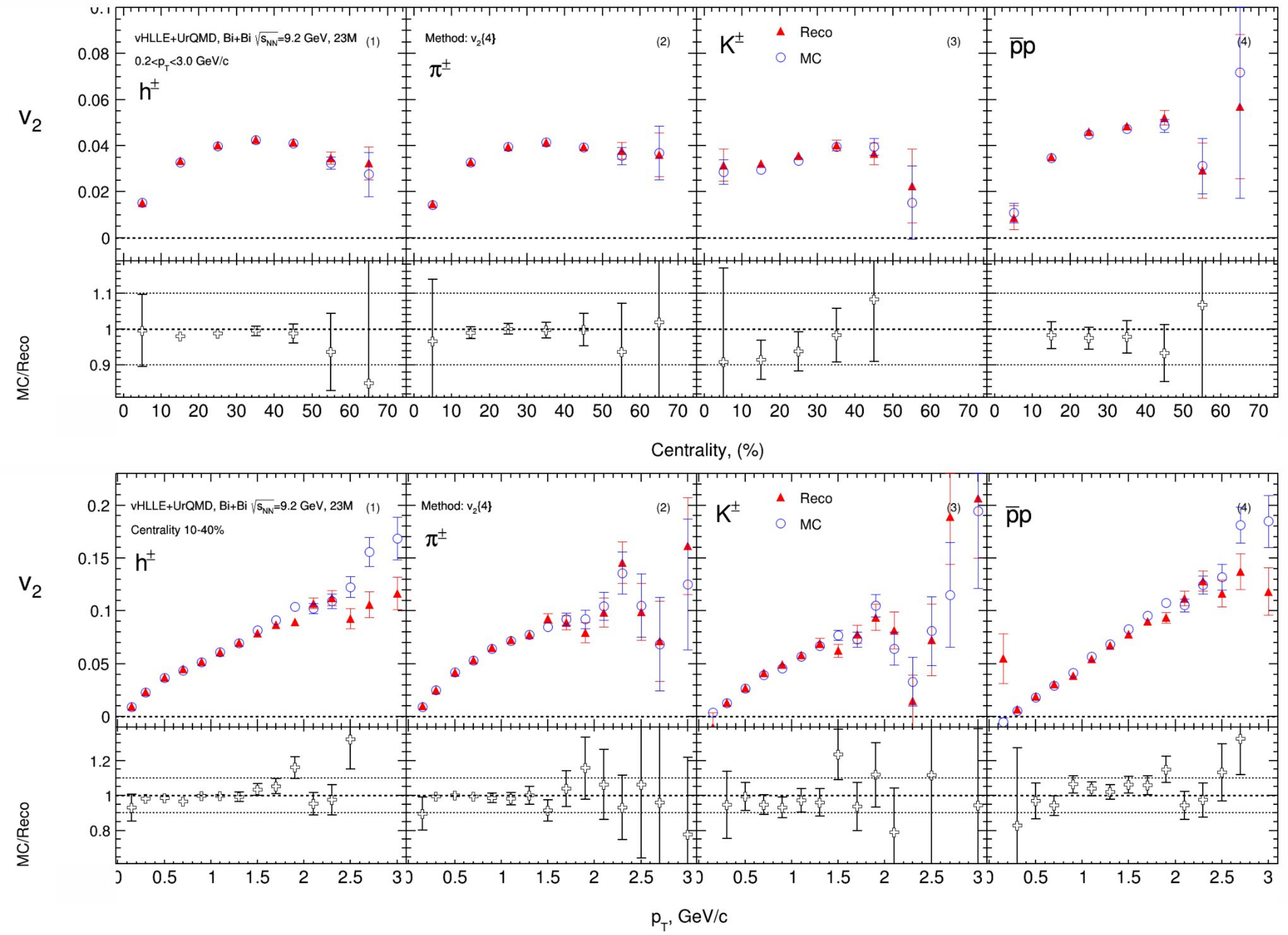
Summary for main topic 2

- **Flow measurements for UrQMD model (req. 25):**
  - Directed and elliptic flow measurements were done using several methods: event plane, scalar product and Q-Cumulant.
  - Results are ready for the second collaboration paper
- **Flow measurements for vHLLE+UrQMD model (req. 32):**
  - Observed outlier events in the distribution Mult vs b - typical for this model
  - Centrality classes have been determined using the Inverse Bayes method. For this model, flow measurements (without cut on Mult vs b) are possible up to 50-60%
  - There is a good agreement between $v_{2,mc}$ and $v_{2,reco}$. But there are differences at large p_T region - contribution from non-flow.
  - Current statistics are not enough for v_3 measurements.

Summary for the main topic 3

- **Performance study for v_n measurements using FFD detector:**
  - Event plane Resolution of FFD is much more smaller than FHCal resolution;
  - Good agreement for 2 and 3 sub event methods
  - FFD has extremely small Resolution for 2-nd harmonic
  - FFD can be used for directed flow measurements
  - FFD needs more statistics than FHCal for elliptic flow measurements due to low resolution
- **Performance study for v_n measurements in MPD-FXT:**
  - For each particle species v_1 and v_2 are consistent with the model signal mostly in backward rapidities
  - Official production for different beam energies ($\sqrt{s_{NN}}$=2.5, 3.0, 3.5 GeV 10-11 M min bias events each) has been requested for the further studies

Comparison of Reco and MC: $v_2\{4\}$



Cuts:

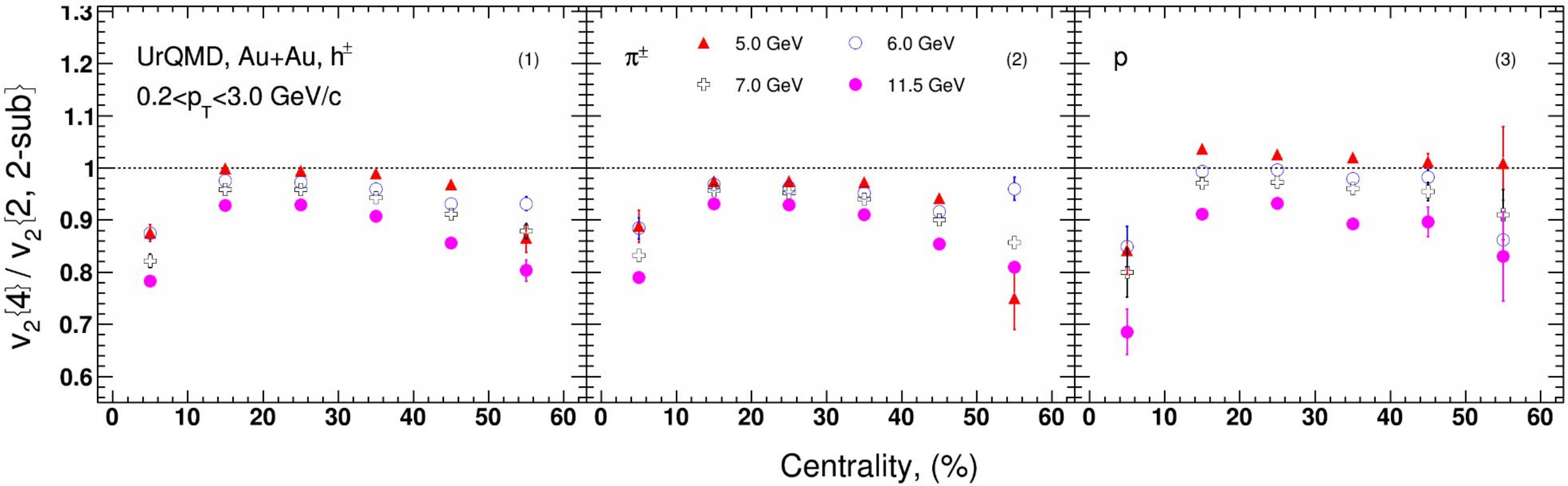
- Charged particles only
- Primary
- $|\eta|<1.5$
- $\Delta\ \eta= 0,1$
- $p_T > 0.2$ GeV/c
- $|DCA|<3\sigma$
- nTPC hits ≥ 16
- PID: PDG code

❑ good agreement of the $v_{2,mc}$ with $v_{2,reco}$ data

❑ The difference at large p_T betwin $v_{2,mc}$ and $v_{2,reco}$ is less than for other methods -> Not

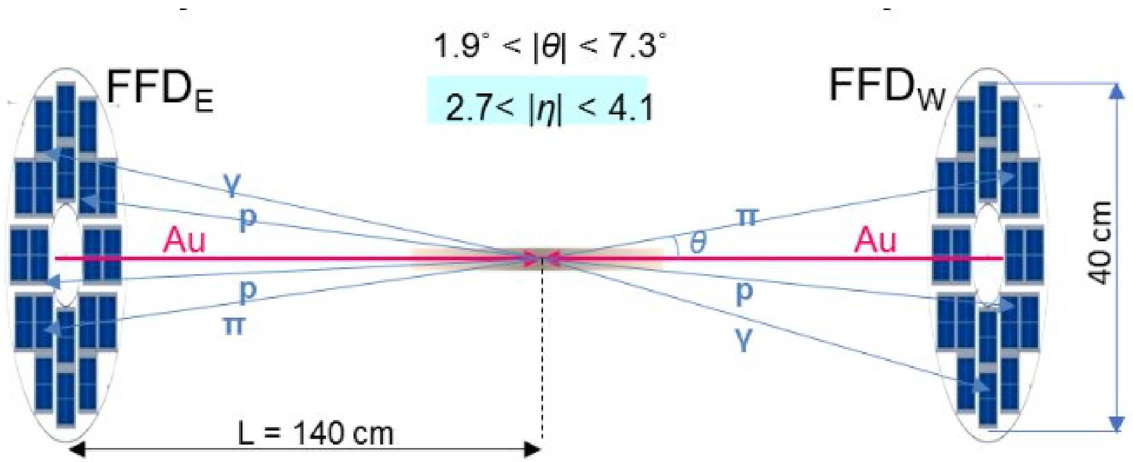
v_2 fluctuations at $\sqrt{s_{NN}}$ = 5 - 11.5 GeV

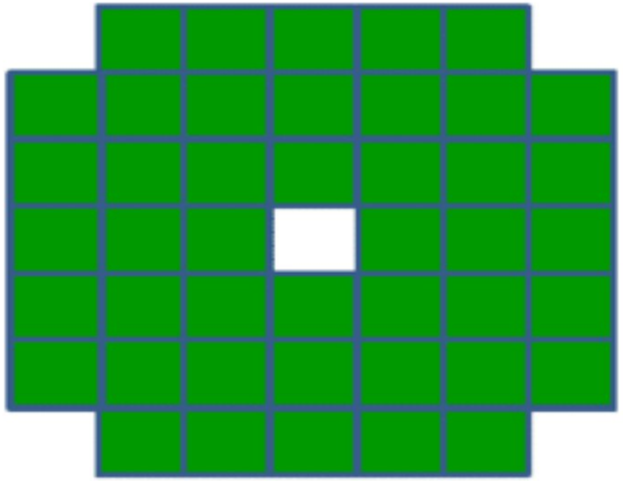
For more details see A.Demanov's talk on ISHEP-2023



- v_2 fluctuations decrease with decreasing energy more strongly than at $\sqrt{s_{NN}}$ = 11.5-39 GeV
- The energy dependence of the $v_2\{4\}/v_2\{2\}$ is stronger for protons than for pions

FHCal and FFD detectors

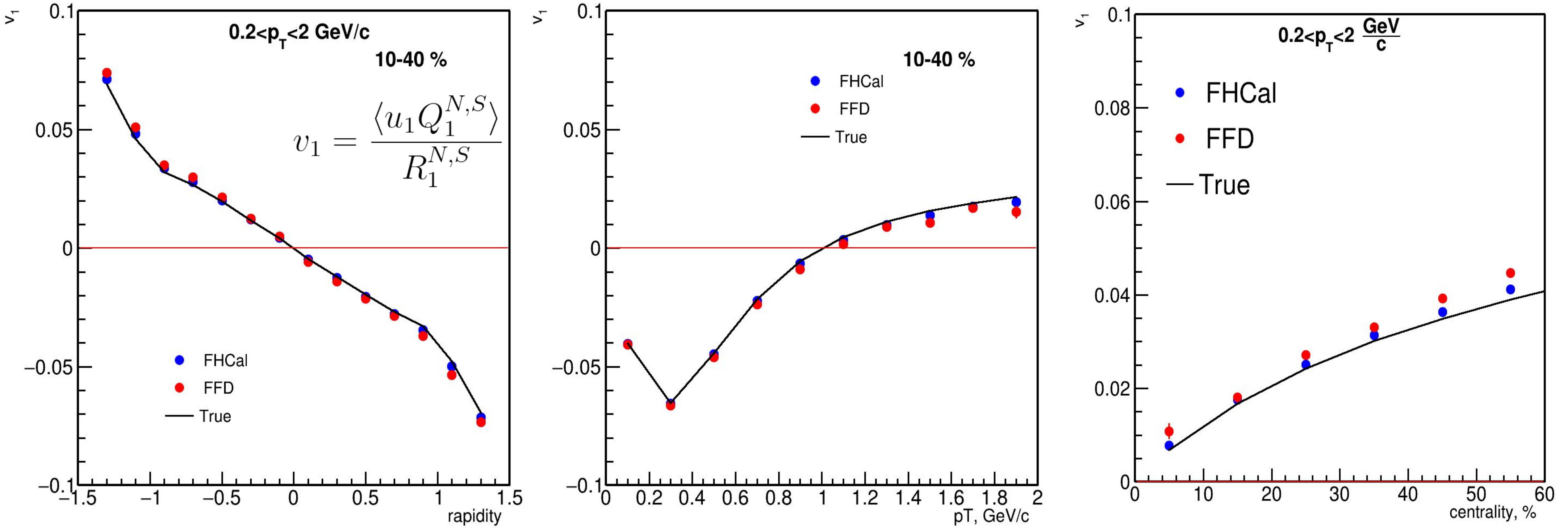




The FFD consists of two sets of Cherenkov counters located at ±140 cm from the nominal interaction point. Each set has 20 physical detectors with 4 read-out channels each. As a result, the total number of read-out channels is 2 sides 80 channels = 160 channels.

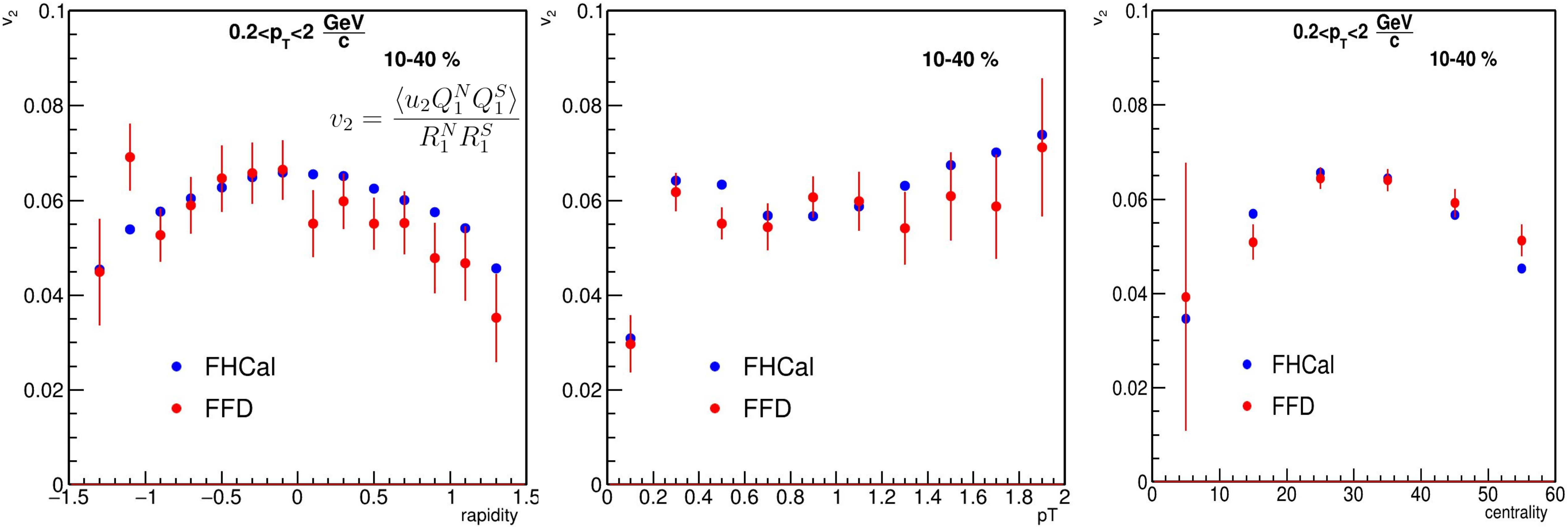
FHCal consists of two sets of hadron calorimeters in pseudorapidity region $2<|\eta|<5$
Each set has 44 modules form azimuthal symmetry. Total number of modules 88.

Directed flow of charged hadrons with FHCal and FFD



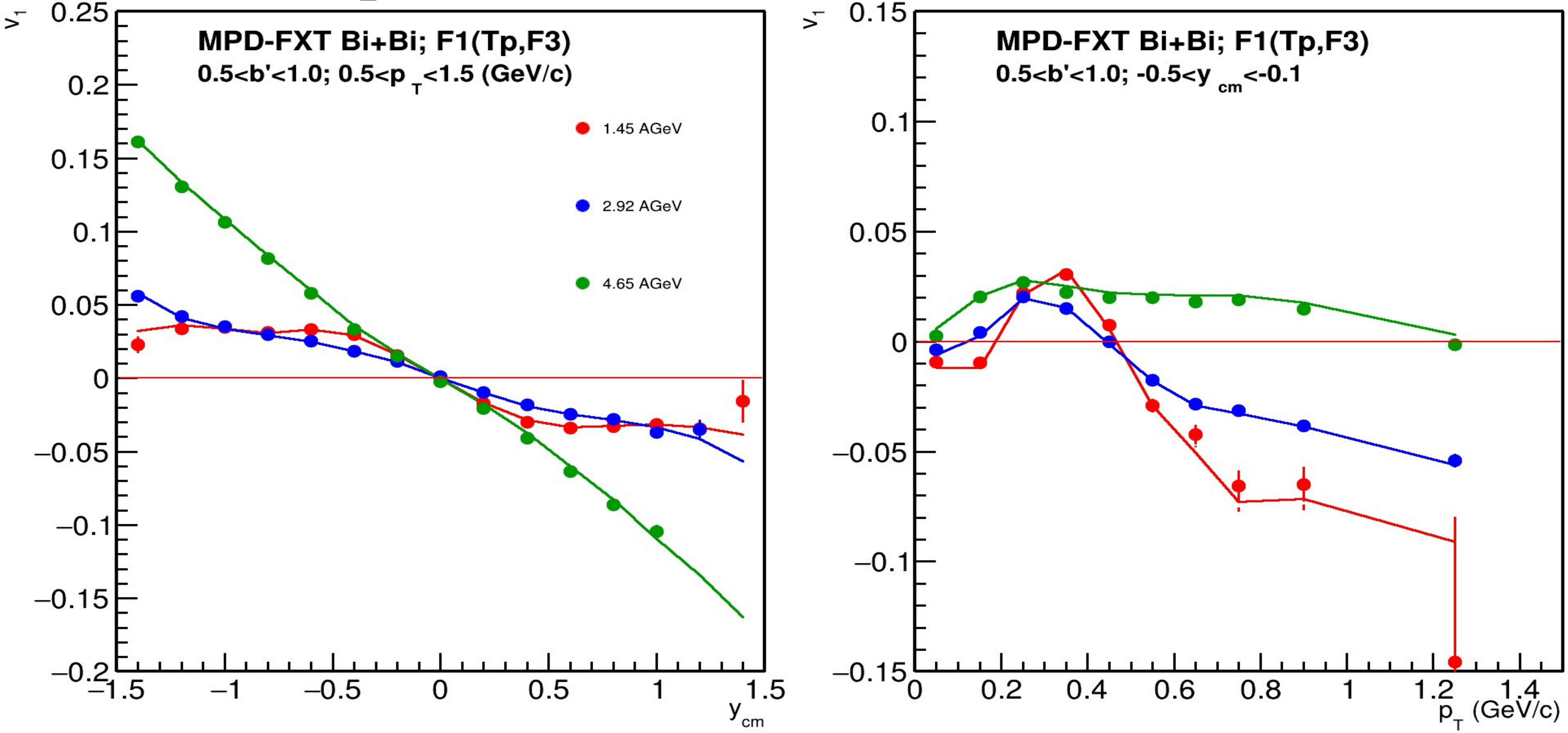
FHCal and FFD have consistent results; both can be used for directed flow measurements.

Elliptic flow of charged hadrons with FHCal and FFD



Due to low Resolution FFD need more statistics than FHCal for elliptic flow measurements.

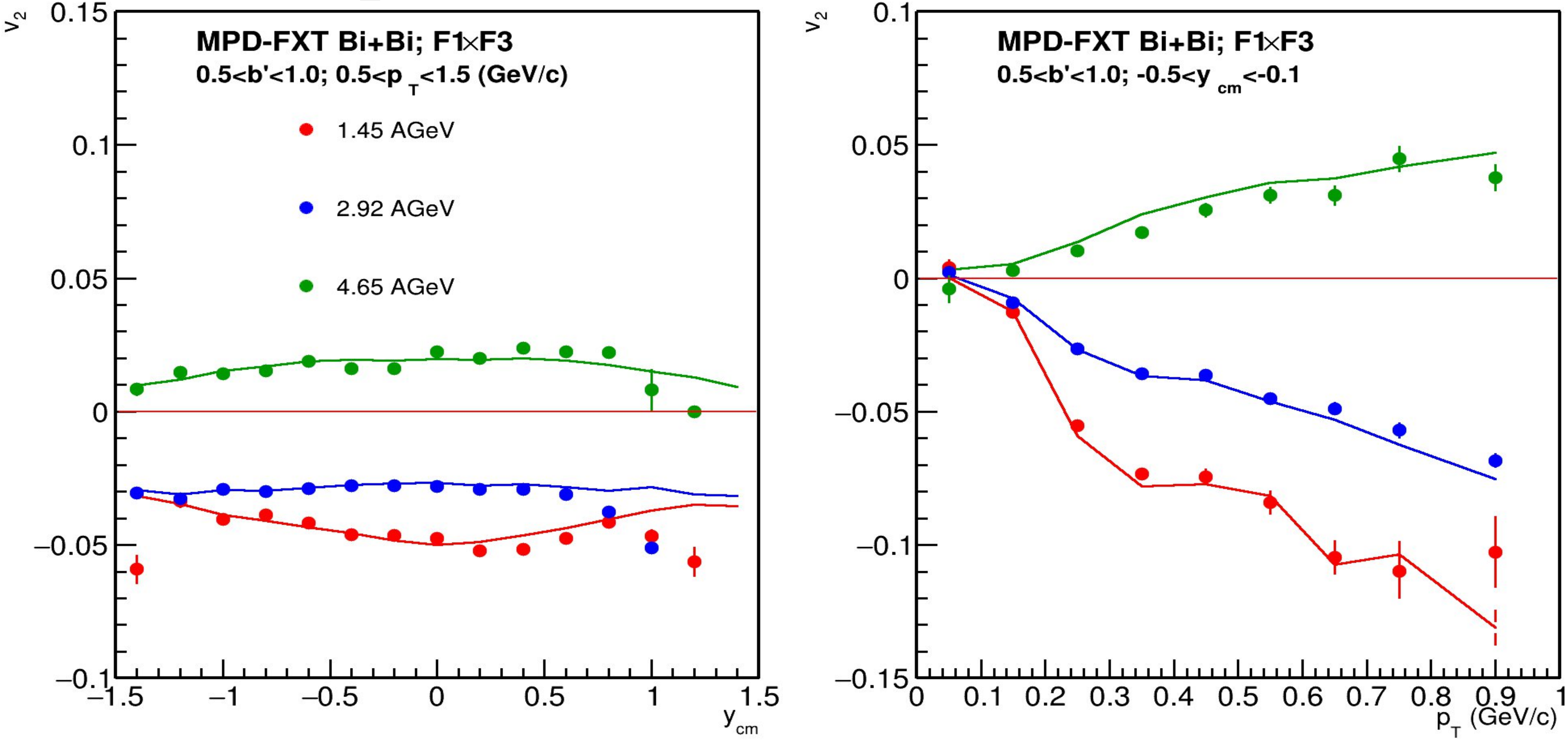
MPD-FXT: v_1 for π^+



v_1 is consistent with model signal for y < 1

No efficiency corrections were applied yet

MPD-FXT: v_2 for π^+



v_2 is consistent with model signal for y < 0.5

No efficiency corrections were applied yet