Performance study of the anisotropic flow measurements of identified charged hadrons with fixed-target mode of the MPD experiment at NICA

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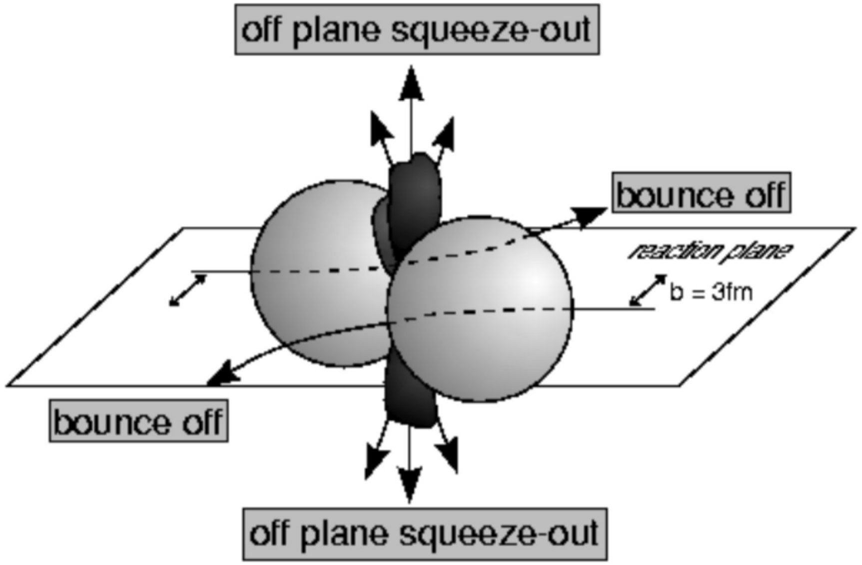
Sensitivity of the collective flow to the EOS



Azimuthal distribution of produced particles with respect to RP:

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

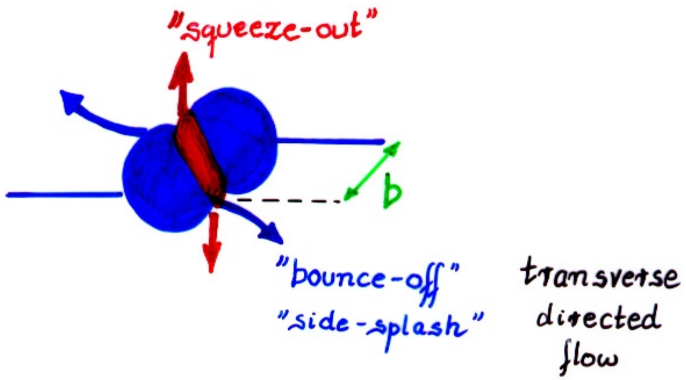
Coefficients of the decomposition are referred to as collective flow

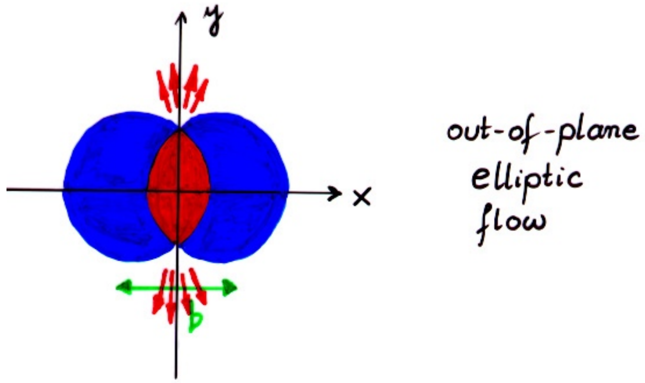
$$v_n = \langle \cos [n(\varphi - \Psi_{RP})] \rangle$$

v_1 is called directed and v_2 is called elliptic flow

Bounce-off

Squeeze-out



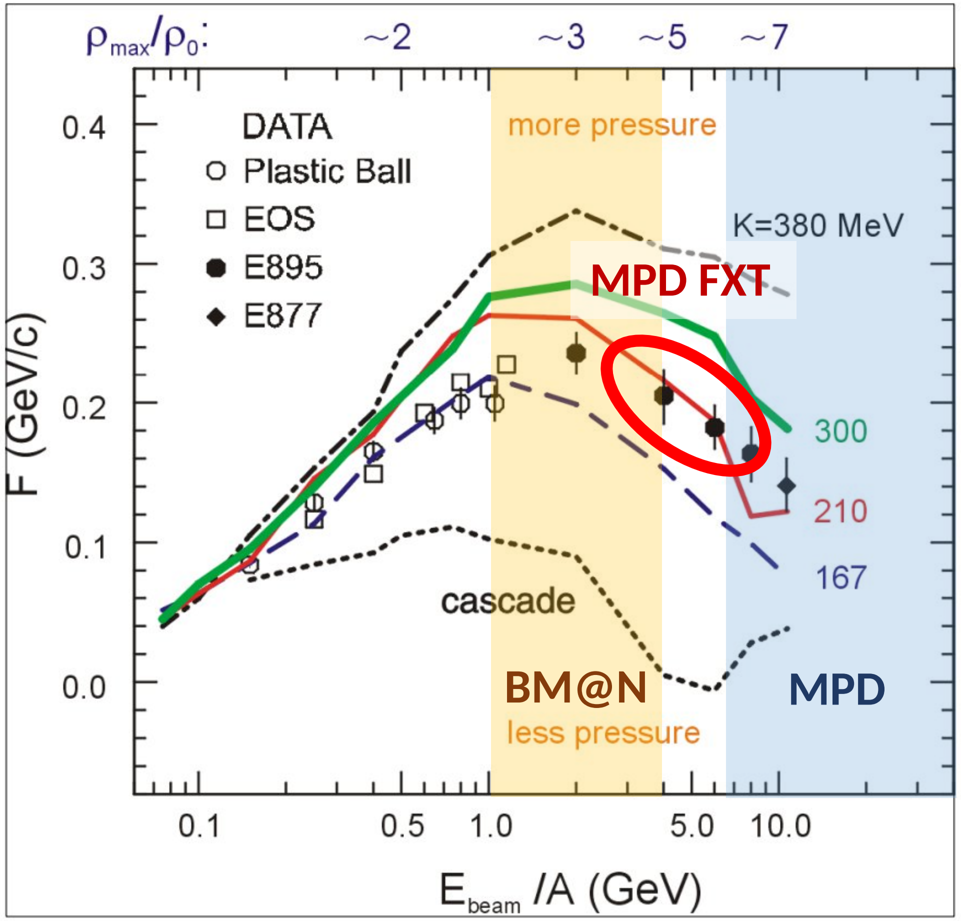


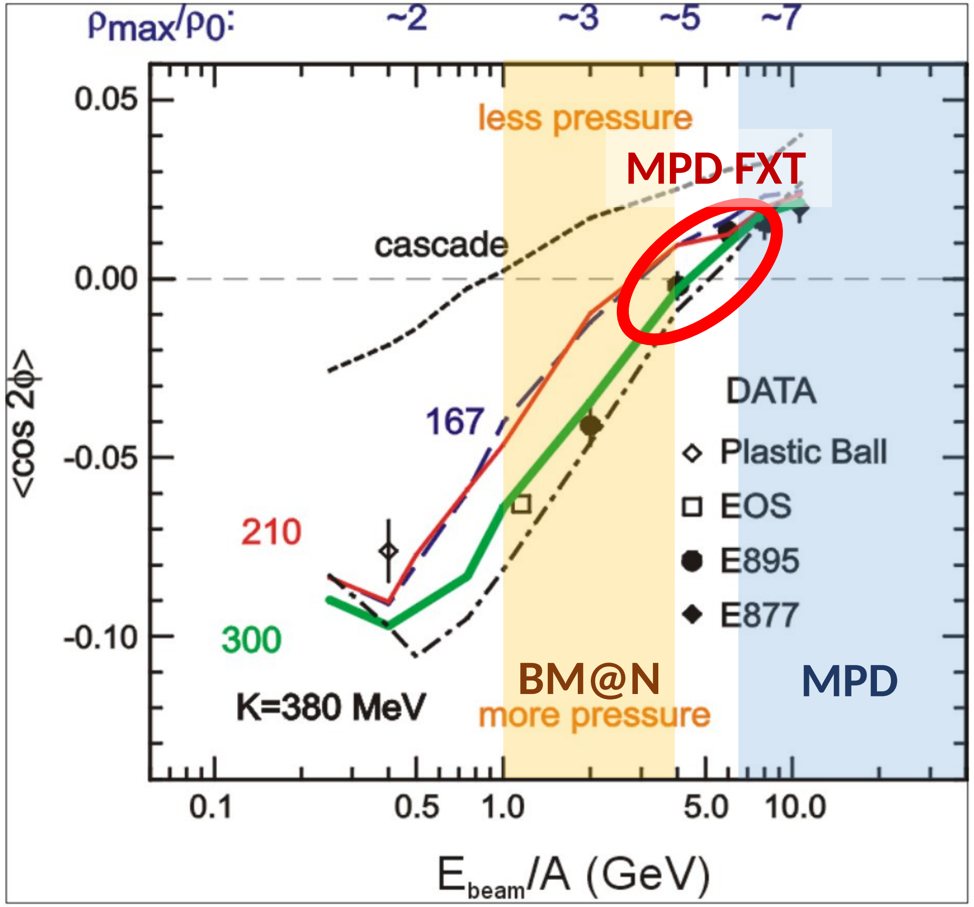
Collective flow is sensitive to:

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

Interpretation of the previous flow data

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

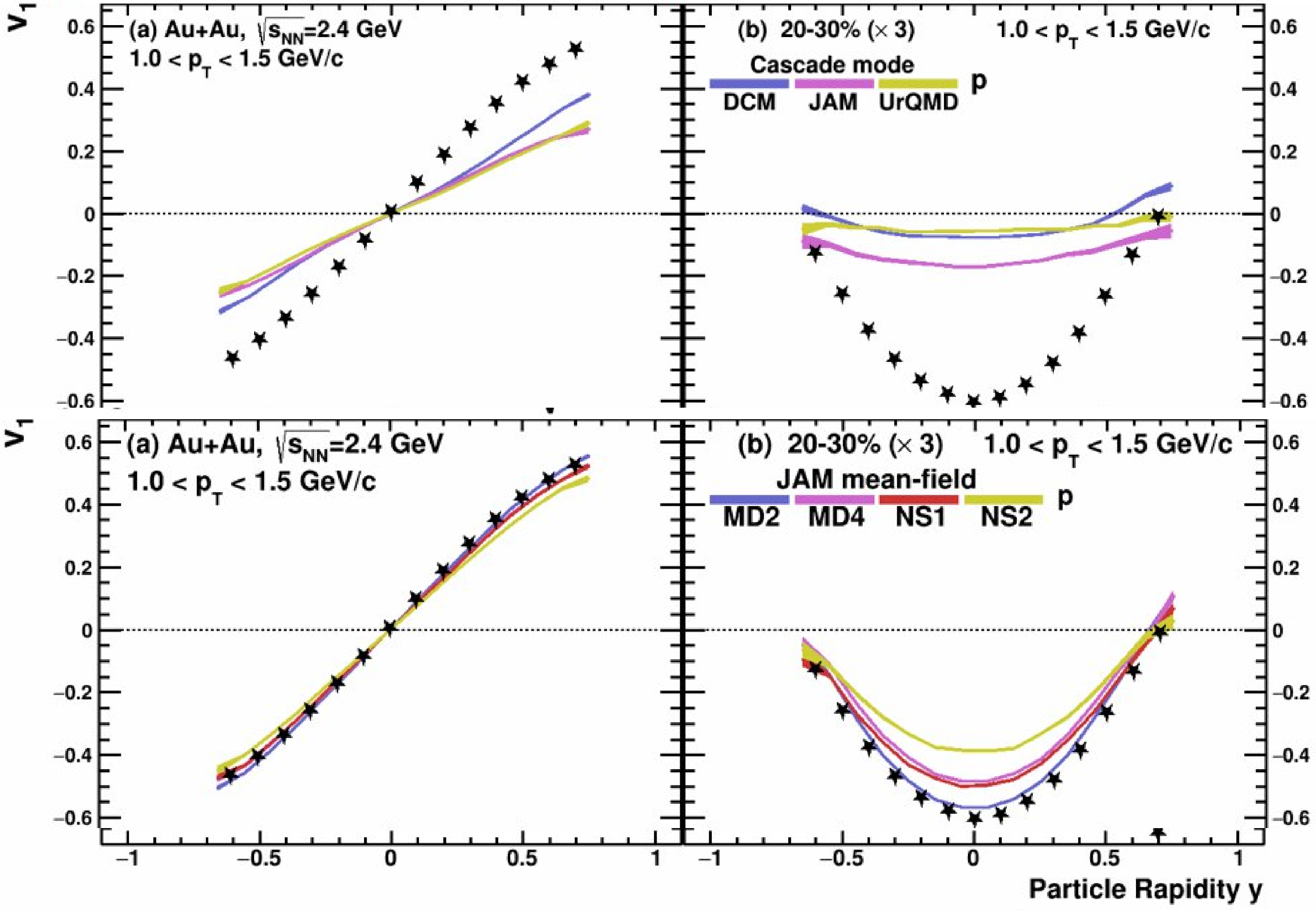




- **The flow data from E895 experiment have ambiguous interpretation:**
  v_1 suggests soft EOS while v_2 corresponds to hard EOS
- **Additional measurements are essential to clarify the previous measurements**

Selecting the model

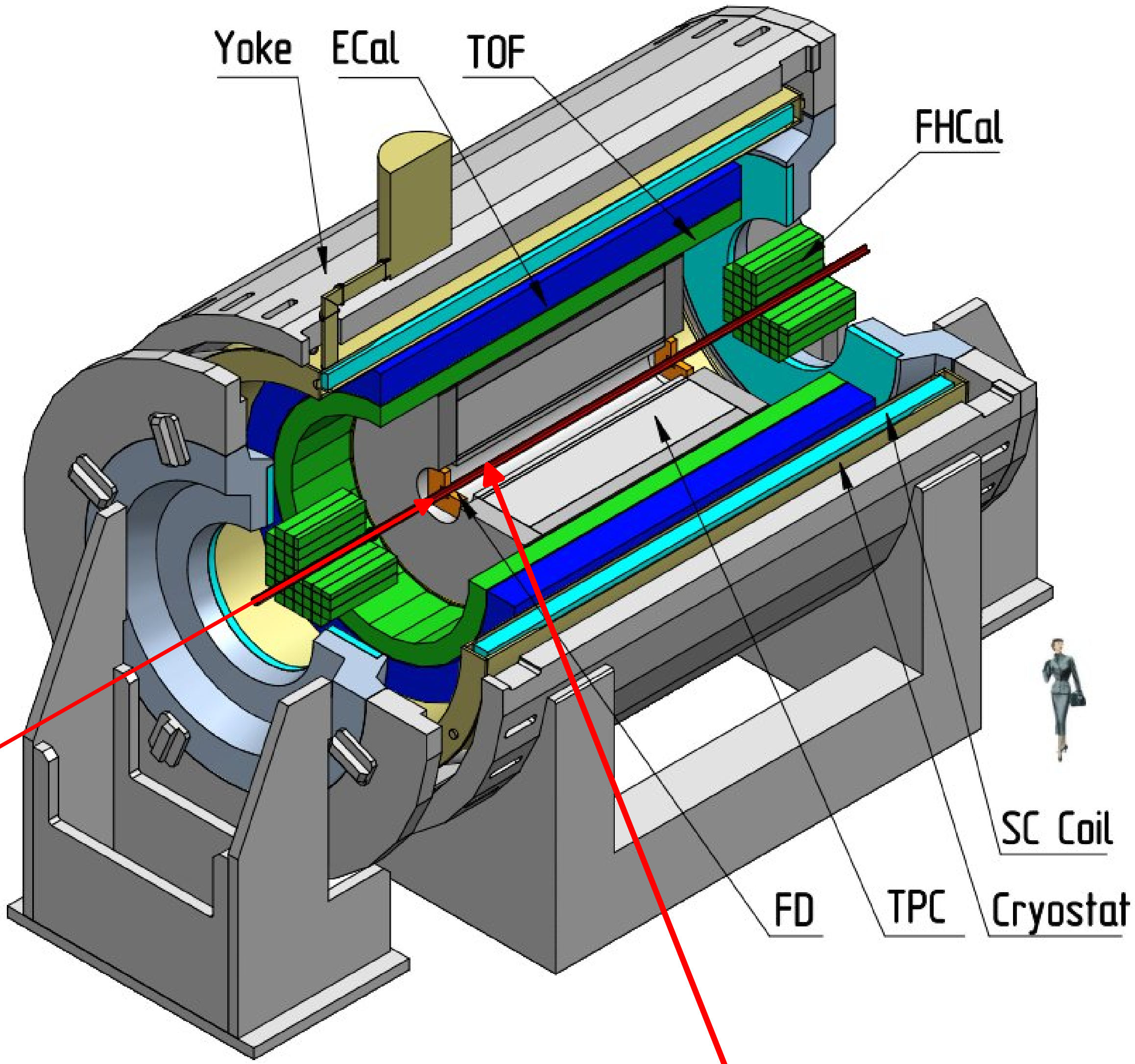
P.Parfenov Particles 5 (2022) 4, 561-579



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

Mean field models reproduce the v_n rather well

MPD in Fixed-Target Mode (FXT)

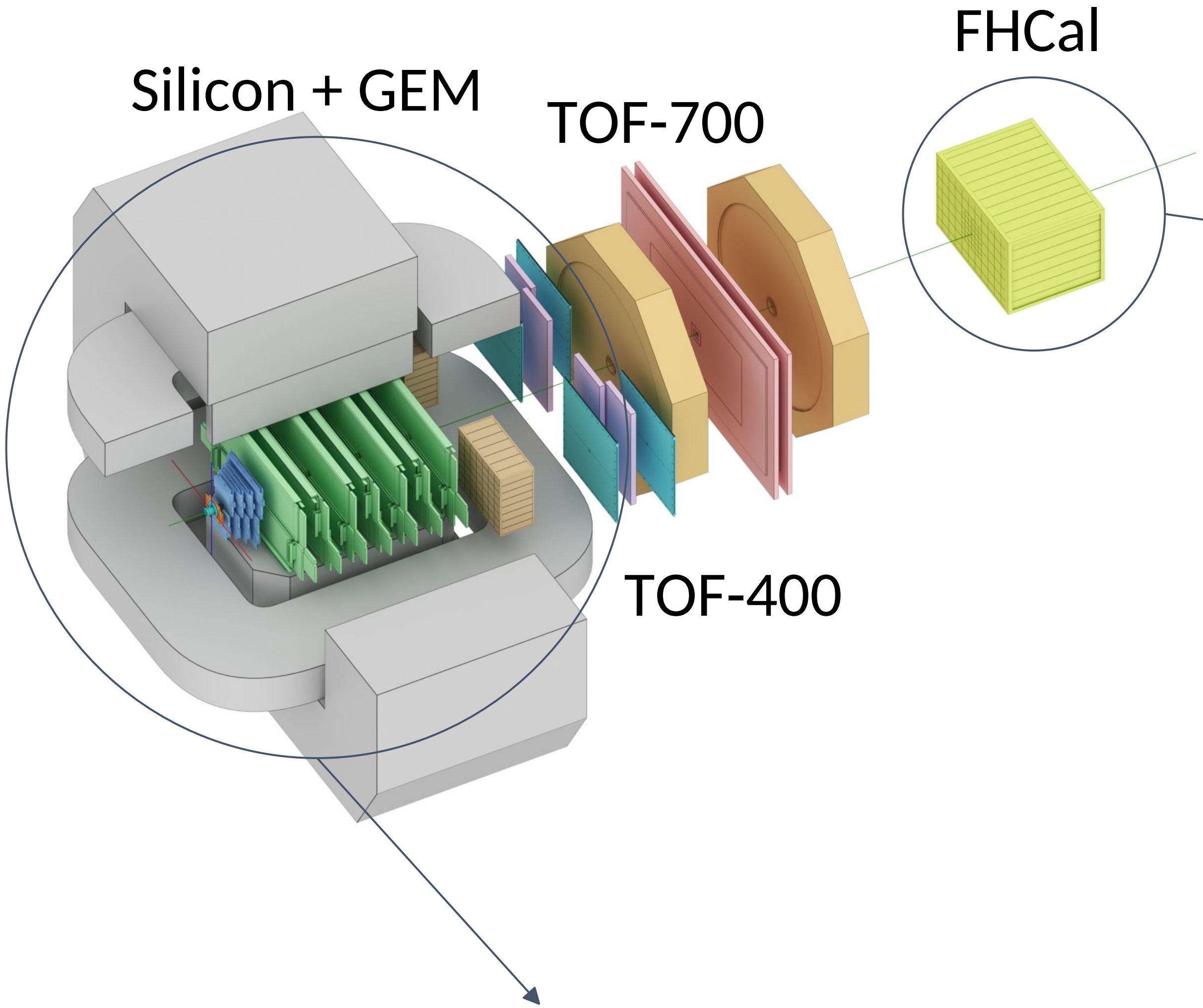


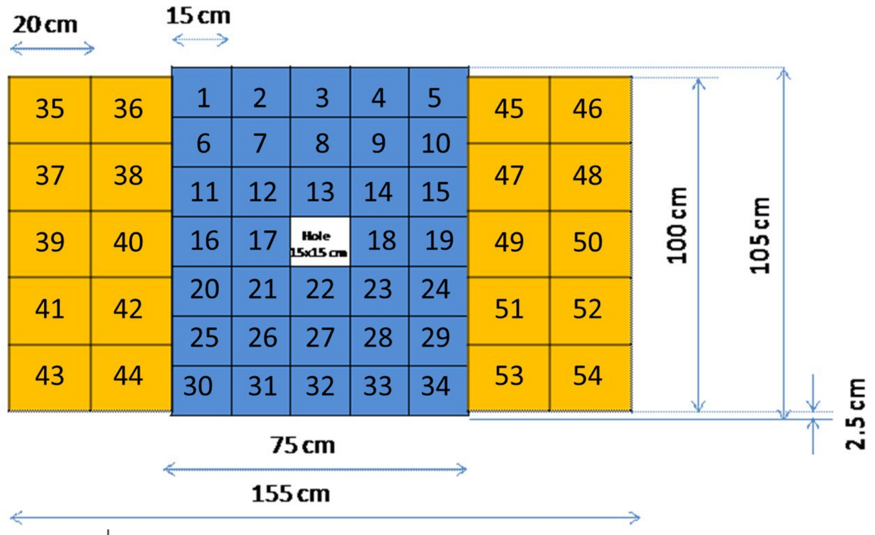
Bea
m

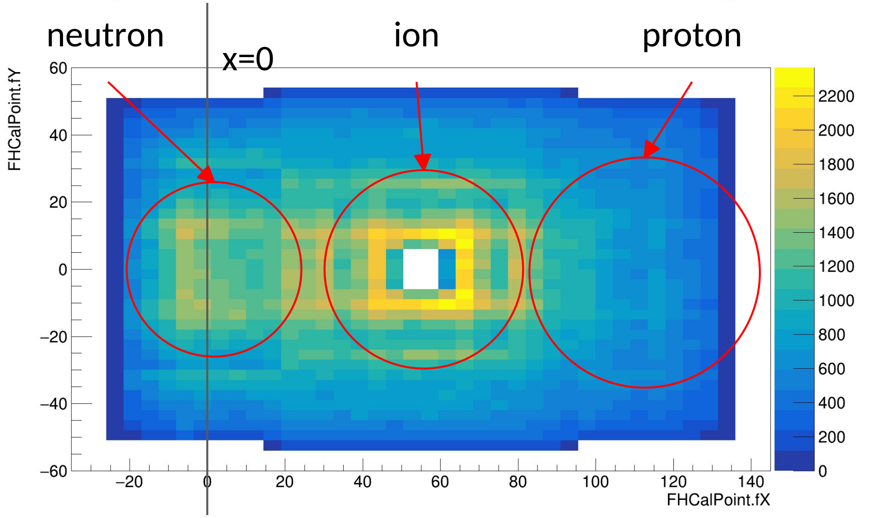
Target (z=-115 cm)

- Model used: UrQMD mean-field
    - Bi+Bi, E_{kin}=1.45 AGeV
- Point-like target
- GEANT4 transport
- Particle species selection via true-PDG code of the associated MC particle

The BM@N experiment (GEANT4 simulation for RUN8)



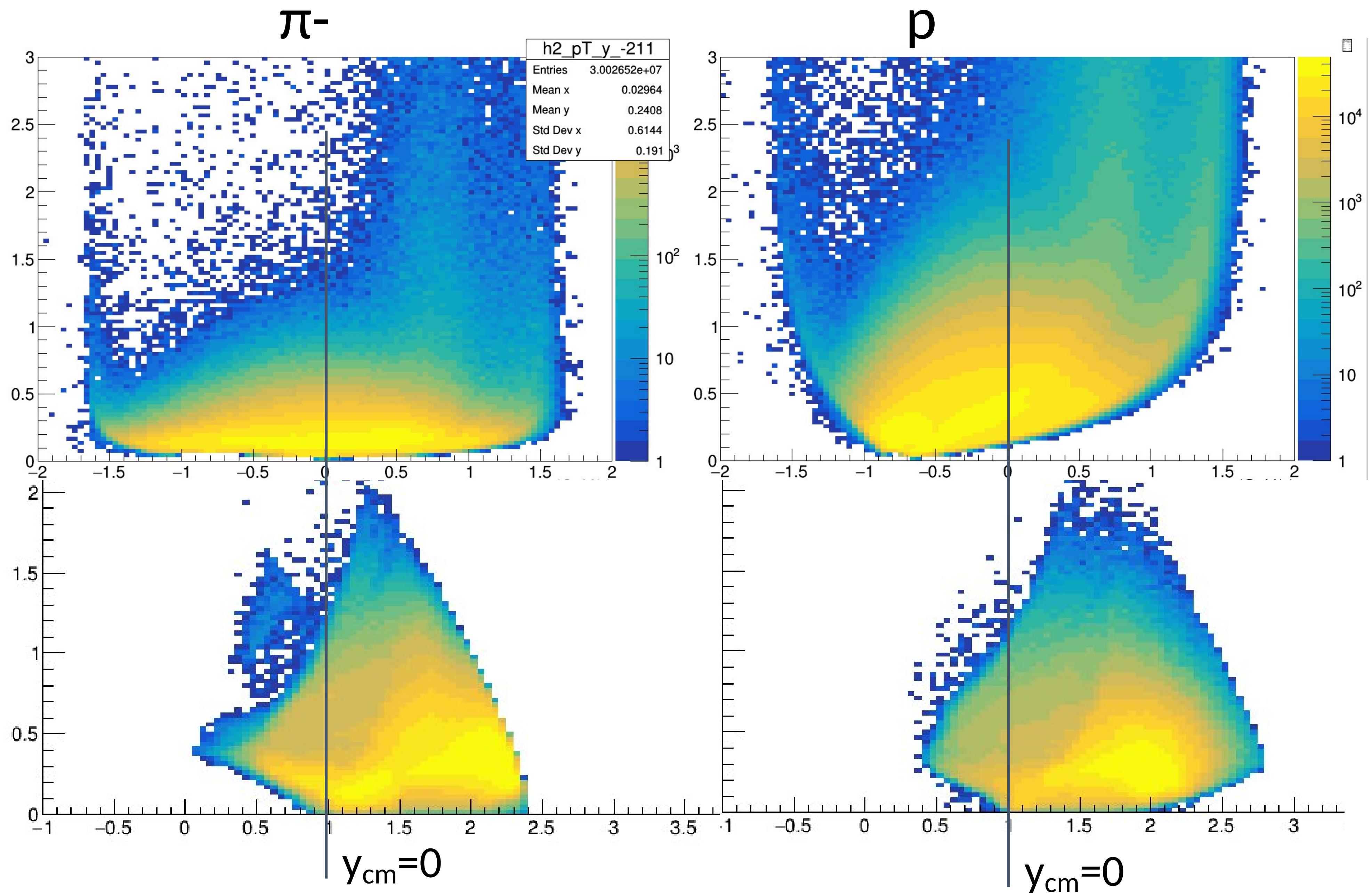




Square-like tracking system within the magnetic field deflecting particles along X-axis

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

BM@N vs MPD: p_T-y acceptance

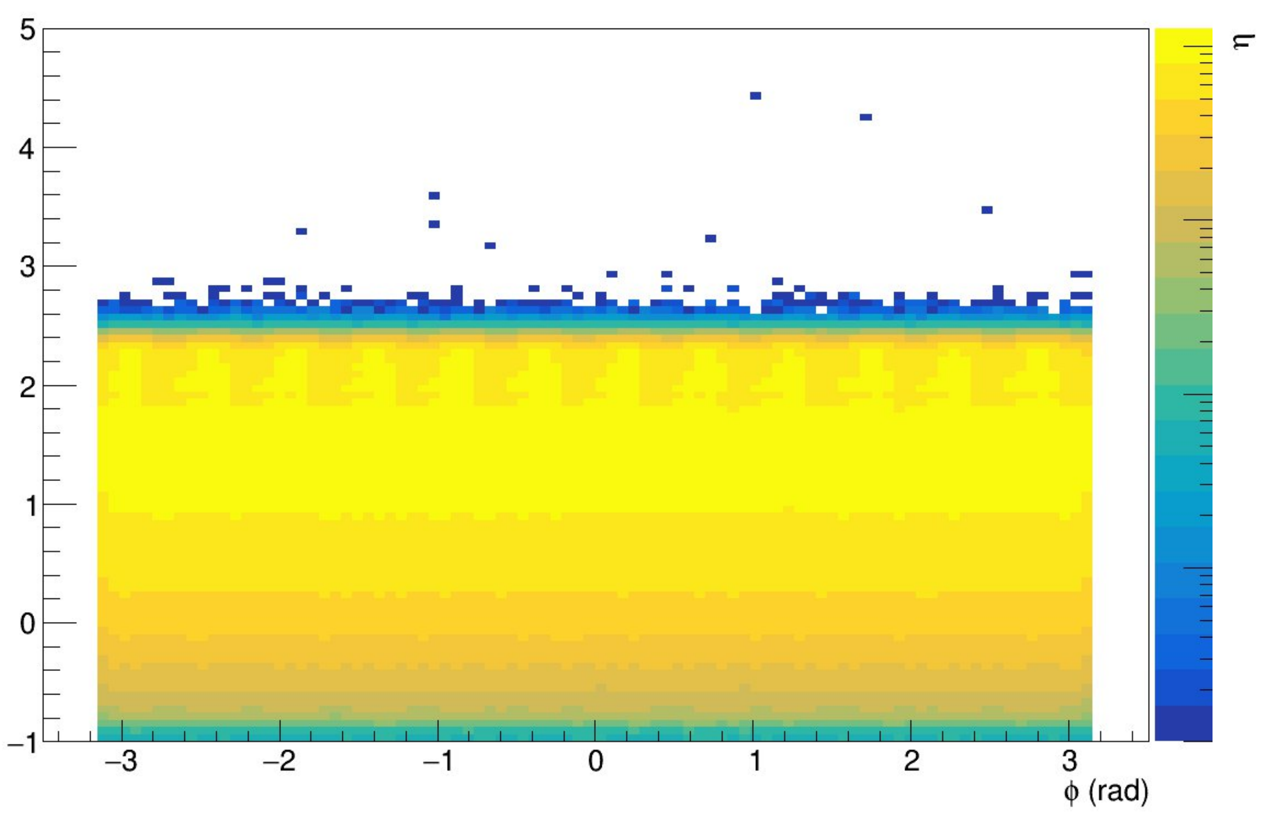


MPD has greater coverage of backward area (even covers projectile spectators) and MPD covers midrapidity region

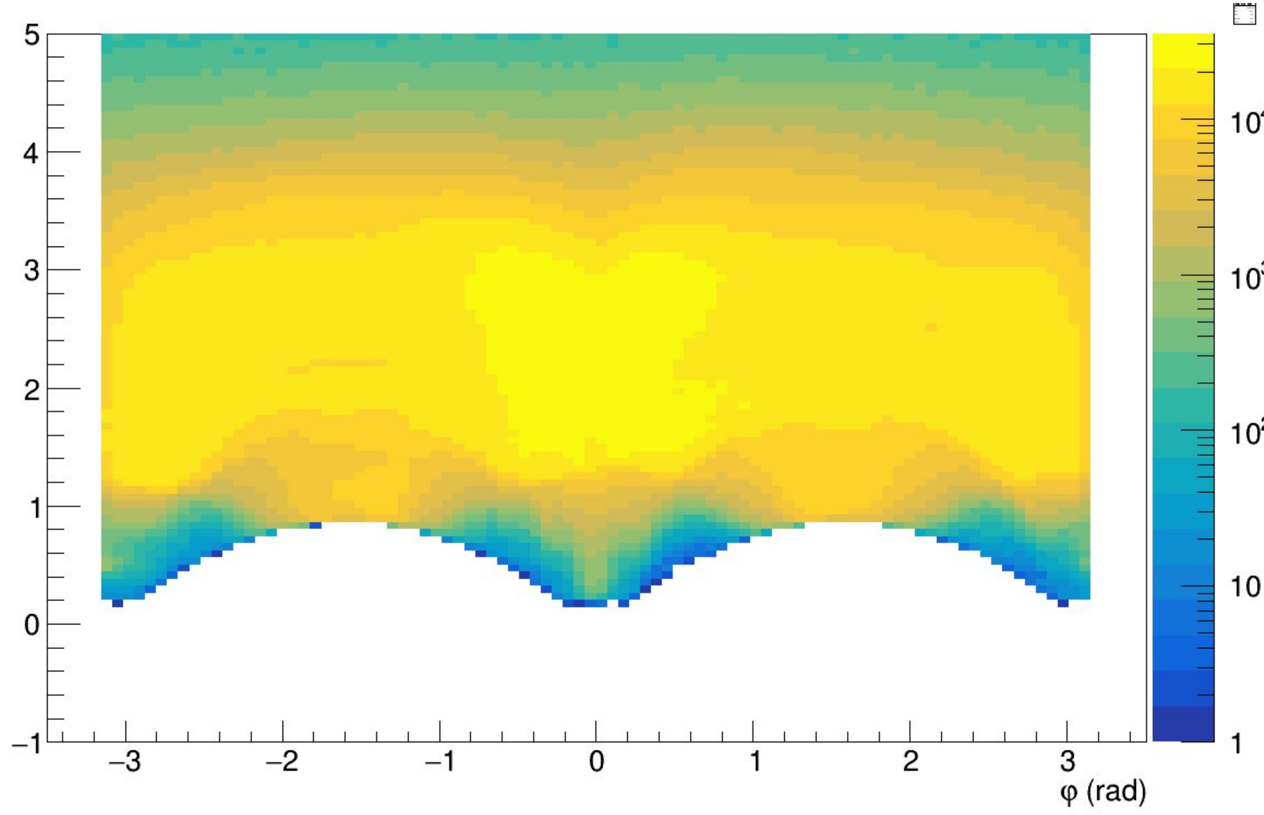
BM@N has greater coverage of forward area

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

Flow vectors

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

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

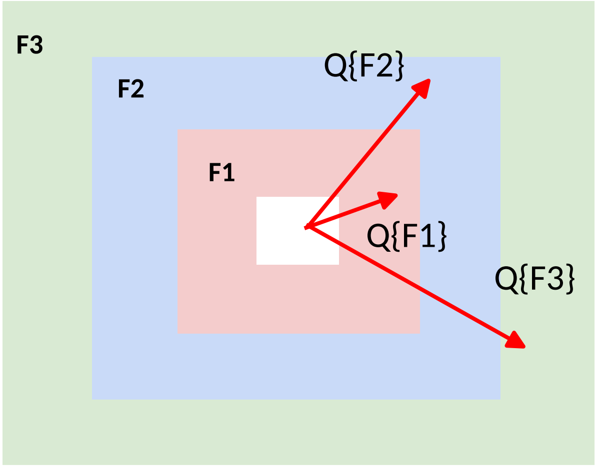
where φ is the azimuthal angle

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

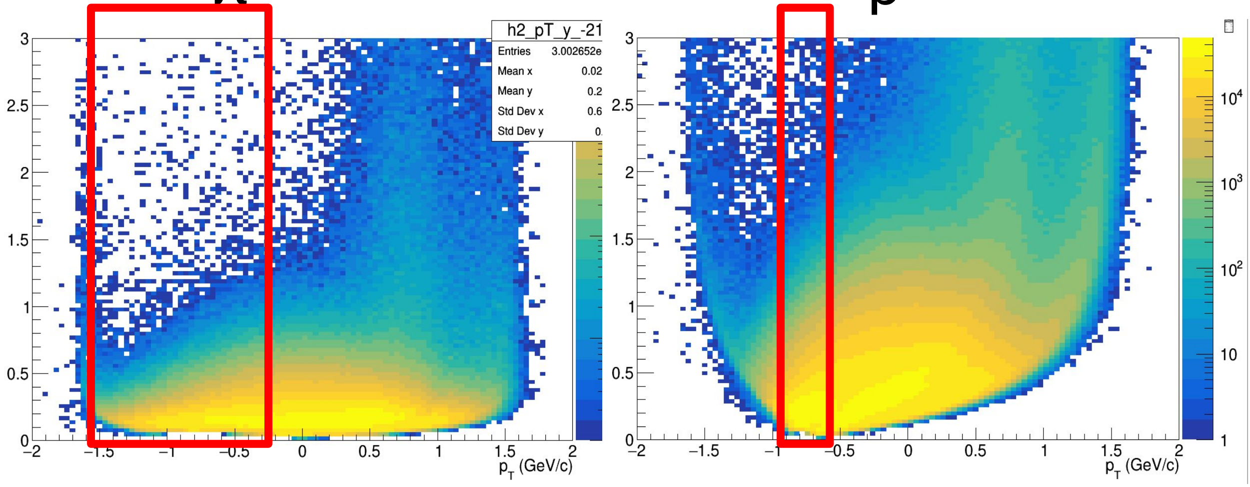
$$Q_n = \frac{\sum_{k=1}^{N} w_n^k u_n^k}{\sum_{k=1}^{N} w_n^k} = |Q_n| e^{in\Psi_n^{EP}}$$

Ψ_n^{EP} is the event plane angle

Modules of FHCal divided into 3 groups

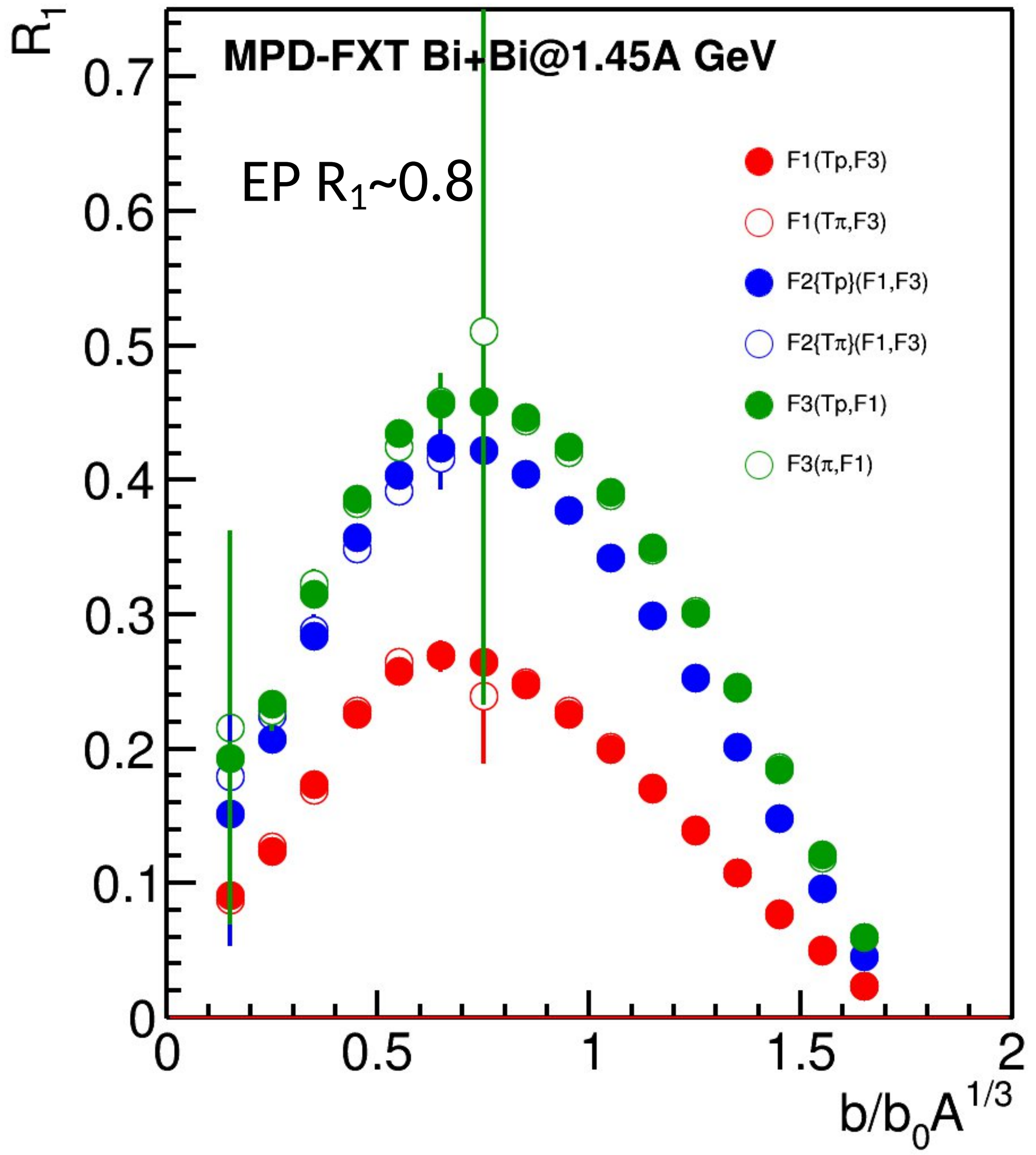


π-   p



Additional subevents from tracks not pointing at FHCal:
Tp: p; -1.0<y<-0.6;
Tπ: π-; -1.5<y<-0.2;

Scalar Product method using FHCal symmetry plane



Tested in HADES: M Mamaev et al 2020 PPNuclei 53, 277–281
M Mamaev et al 2020 J. Phys.: Conf. Ser. 1690 012122

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:

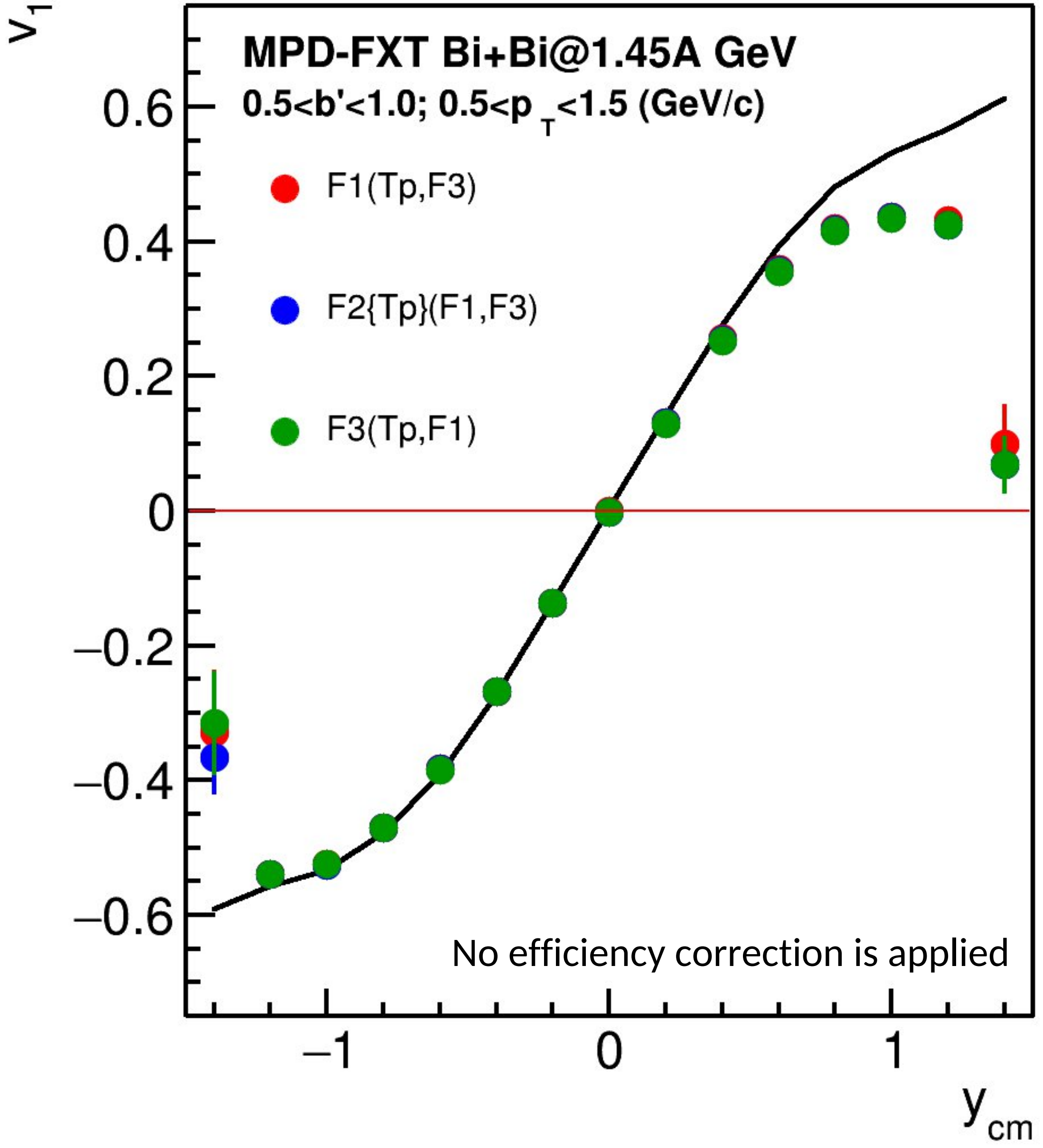
$$R_1^{F1} = \langle \cos(\Psi_1^{F1} - \Psi_1^{RP}) \rangle$$

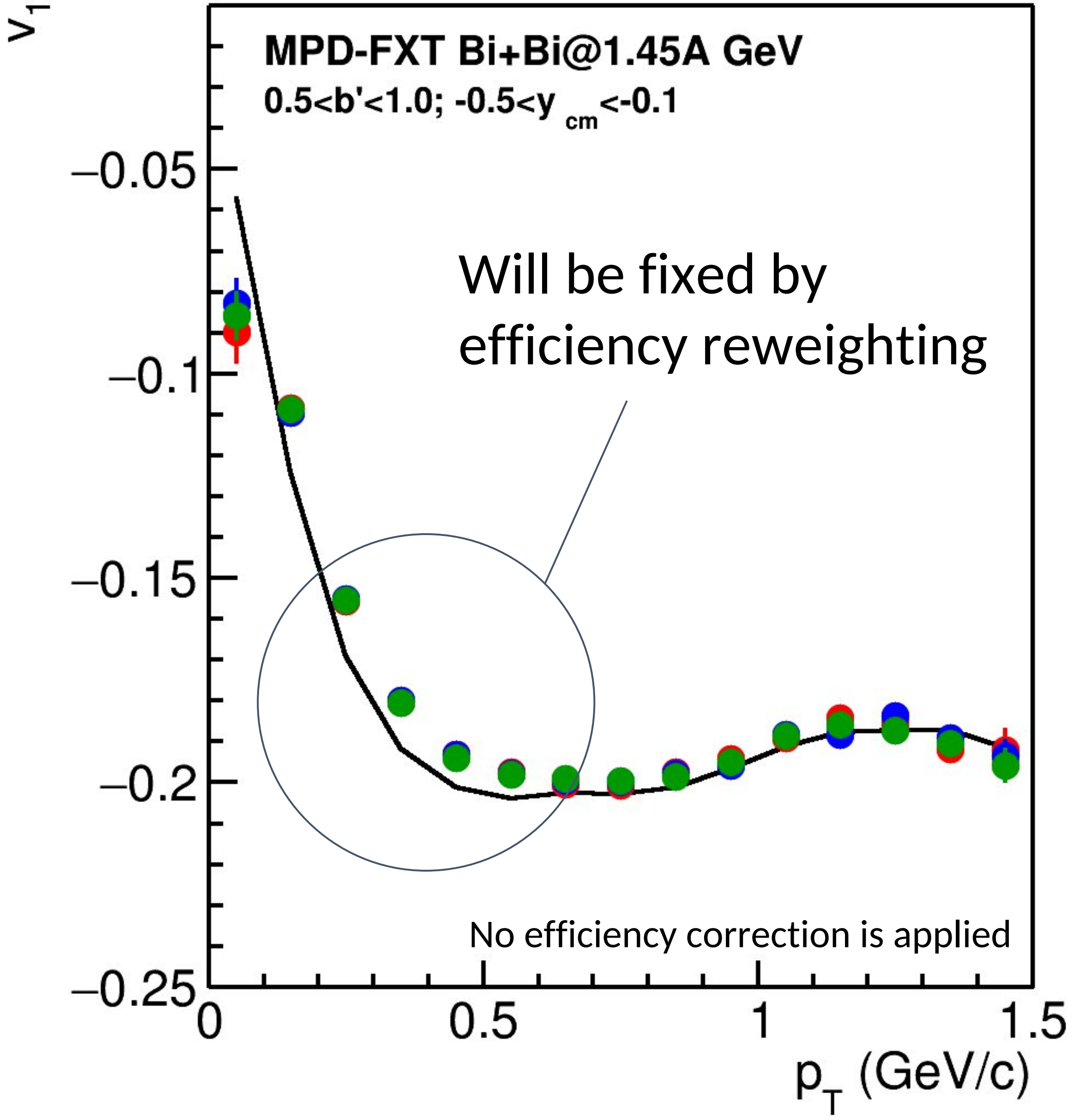
Symbol "F2{Tp}(F1,F3)" means R_1 calculated via (4S resolution):

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

Good agreement between R_1 calculated using different combinations of Q-vectors with significant rapidity separation

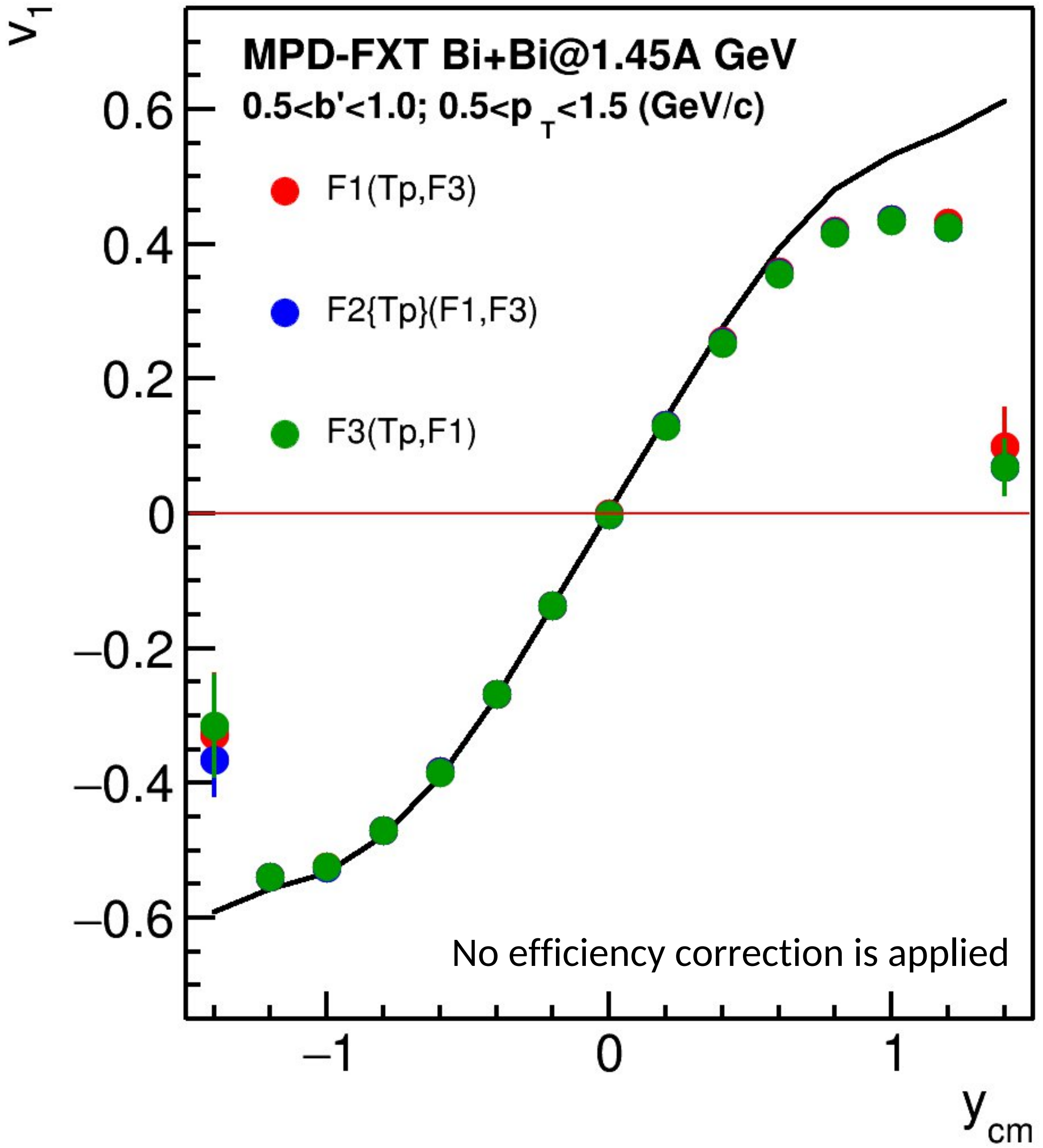
MPD-FXT: v_1 for protons

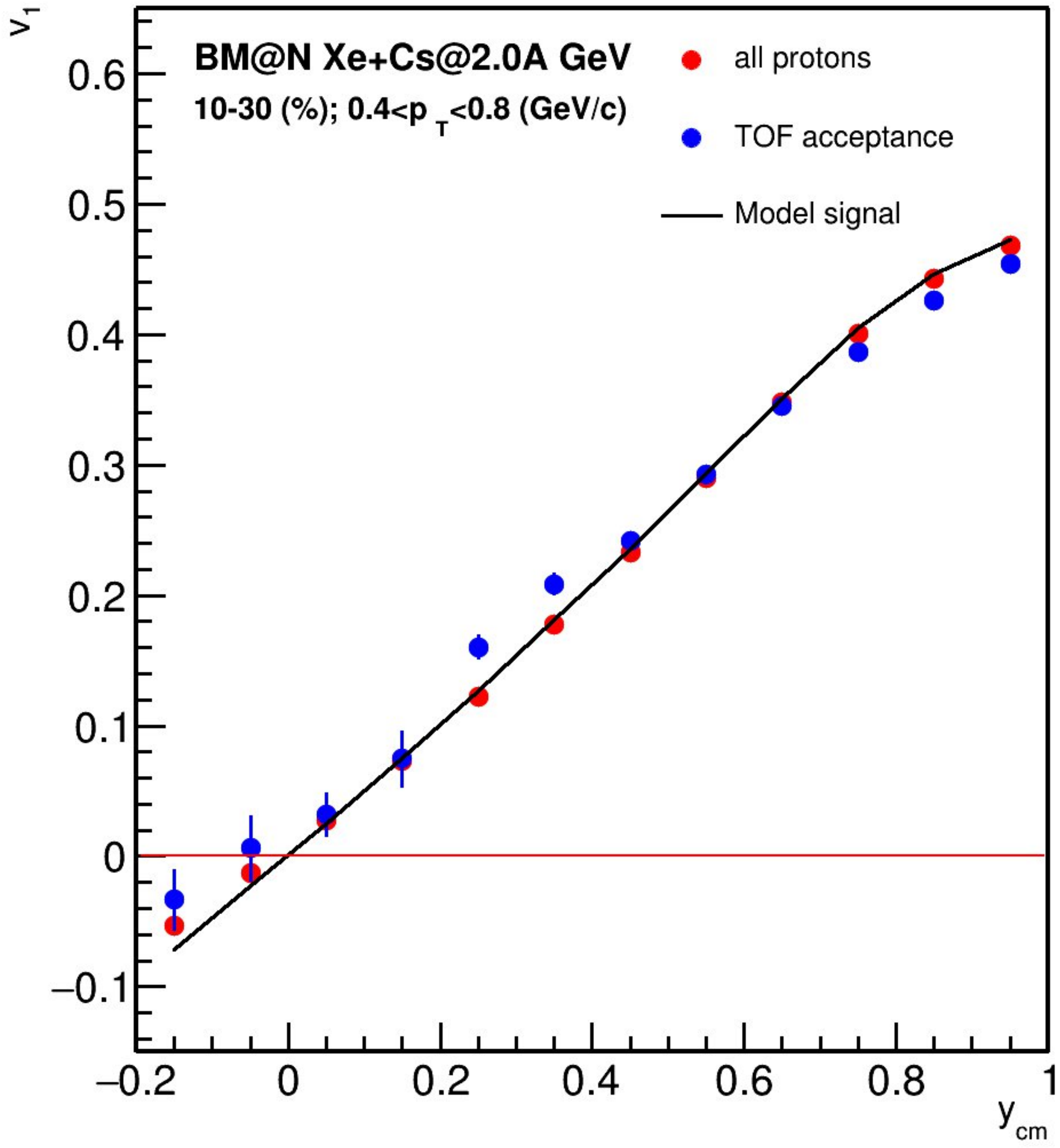




v_1 is consistent with model signal for y < 0.5

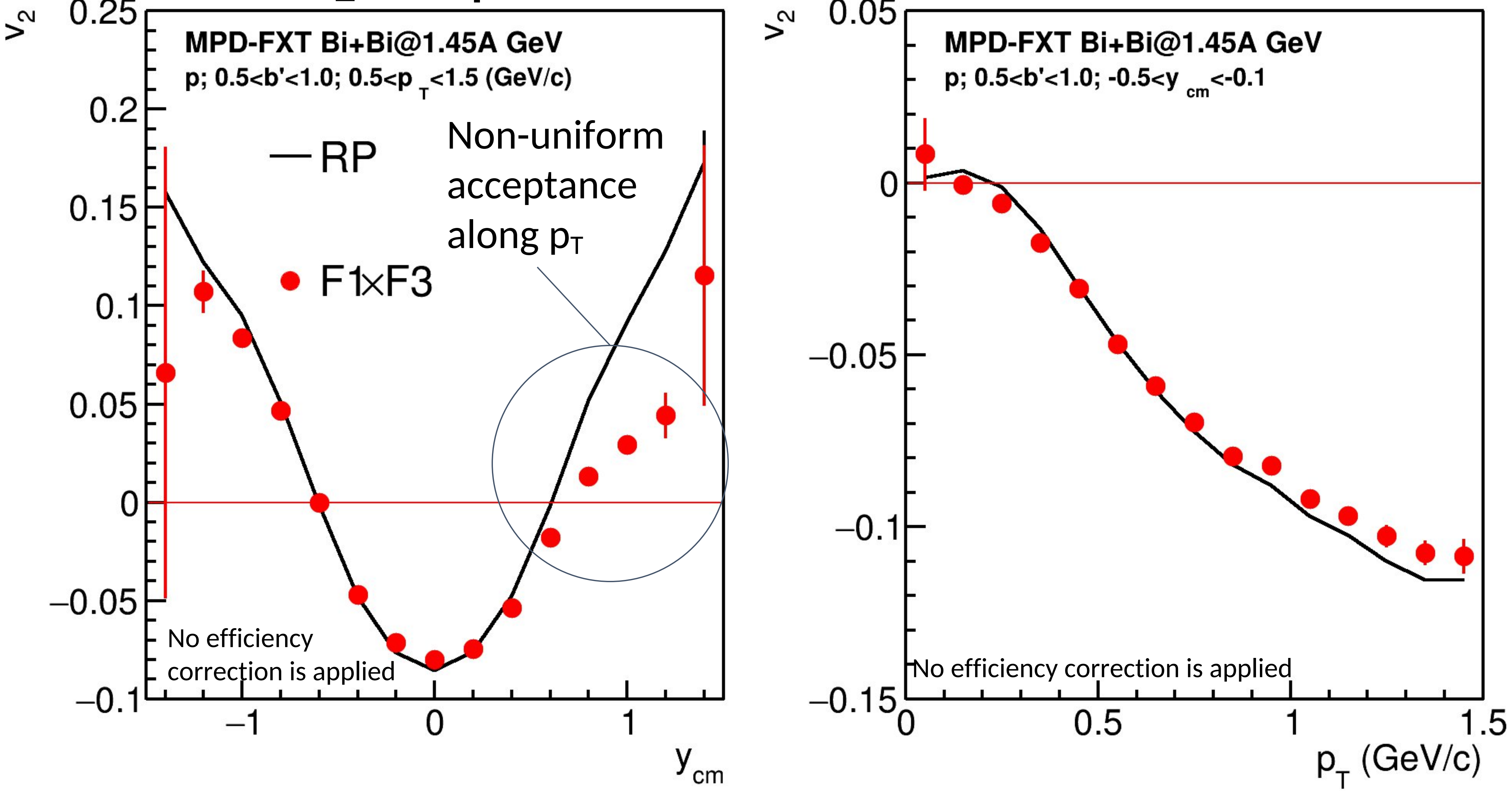
BM@N vs MPD: v_1 vs y for protons





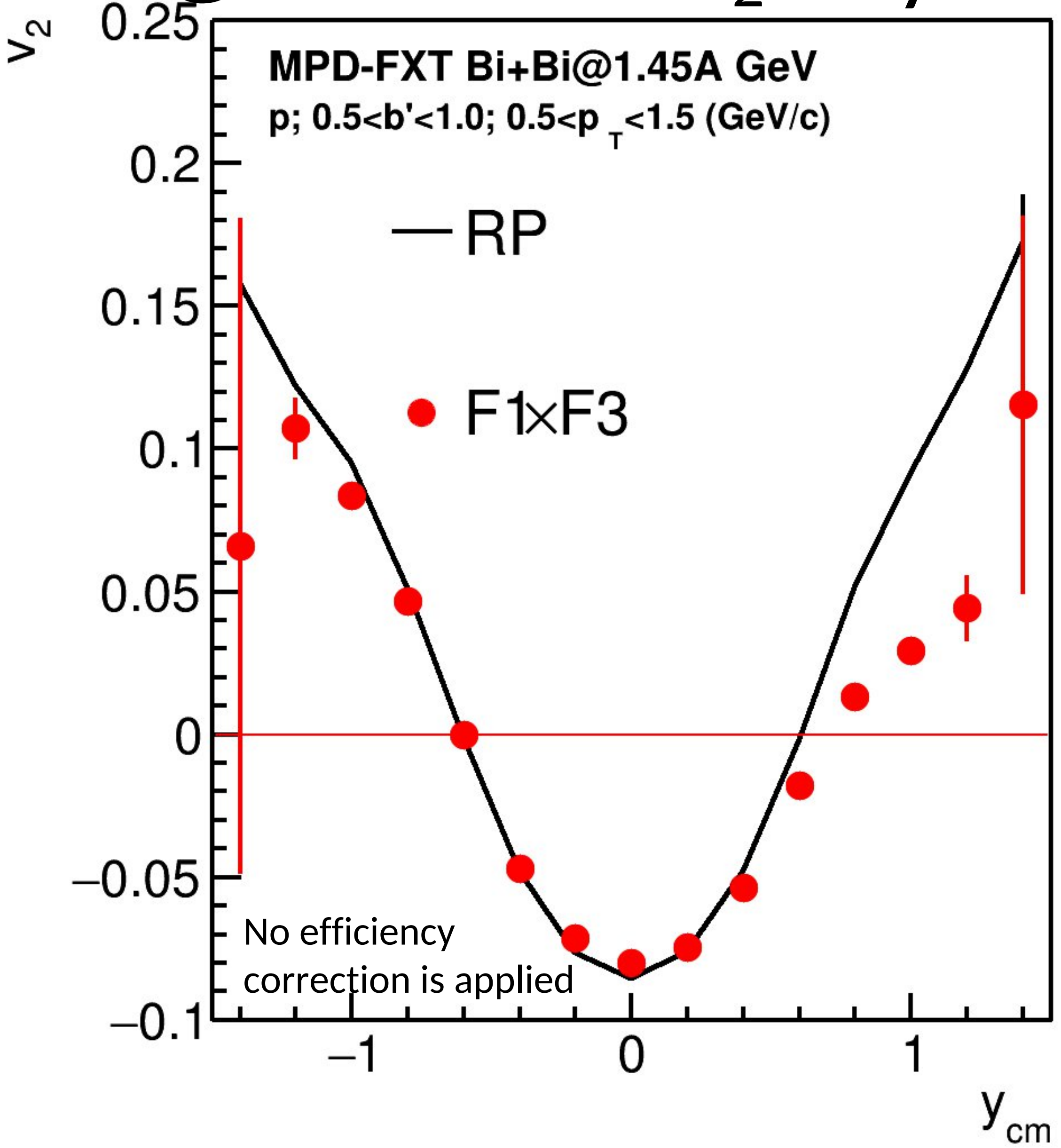
BM@N has better coverage in positive rapidities close to y_{beam}

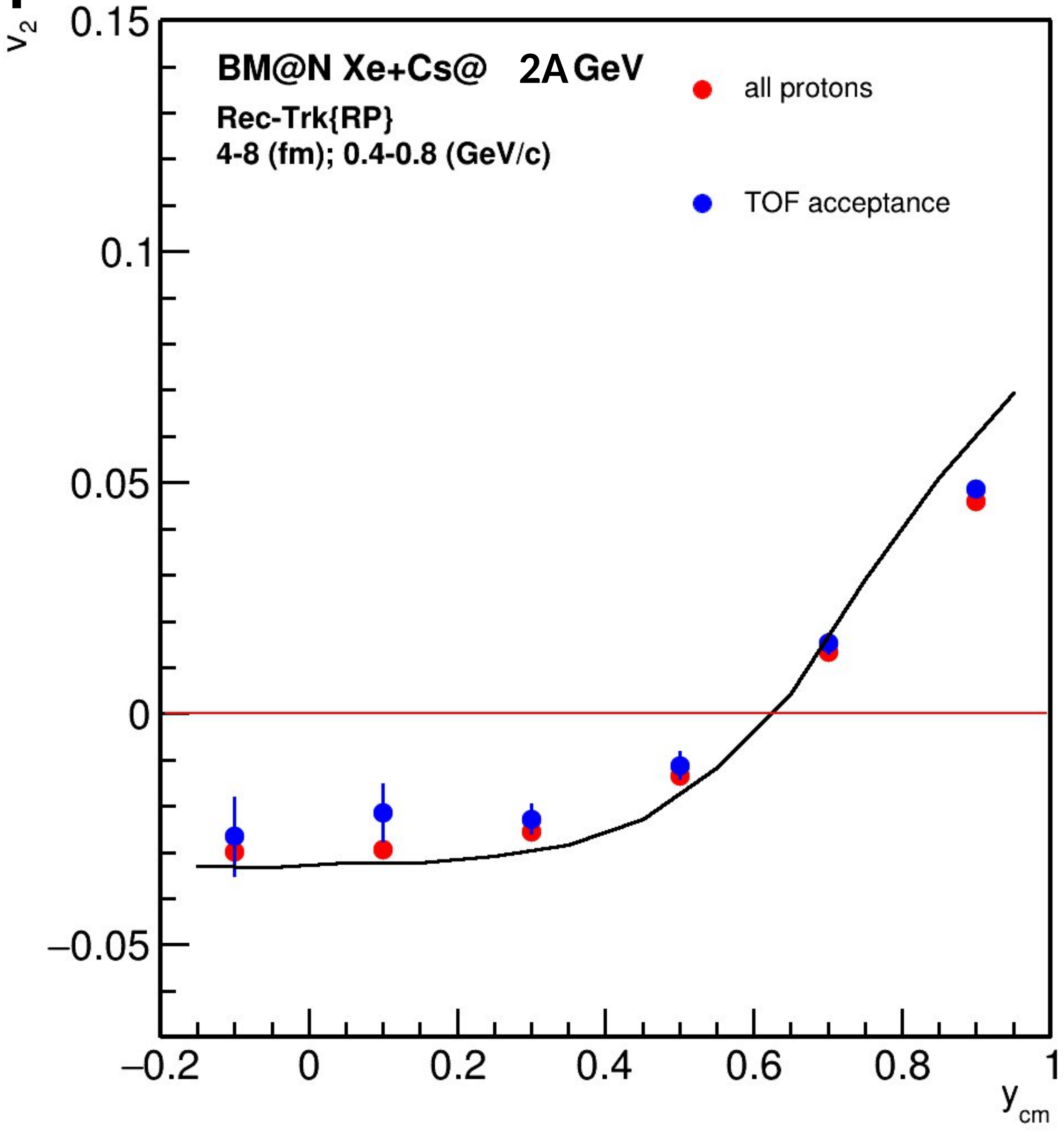
MPD-FXT: v_2 for protons



v_2 is consistent with model signal for y < 0.5

BM@N vs MPD: v_2 vs y for protons





BM@N has better coverage in positive rapidities close to y_{beam}

Summary

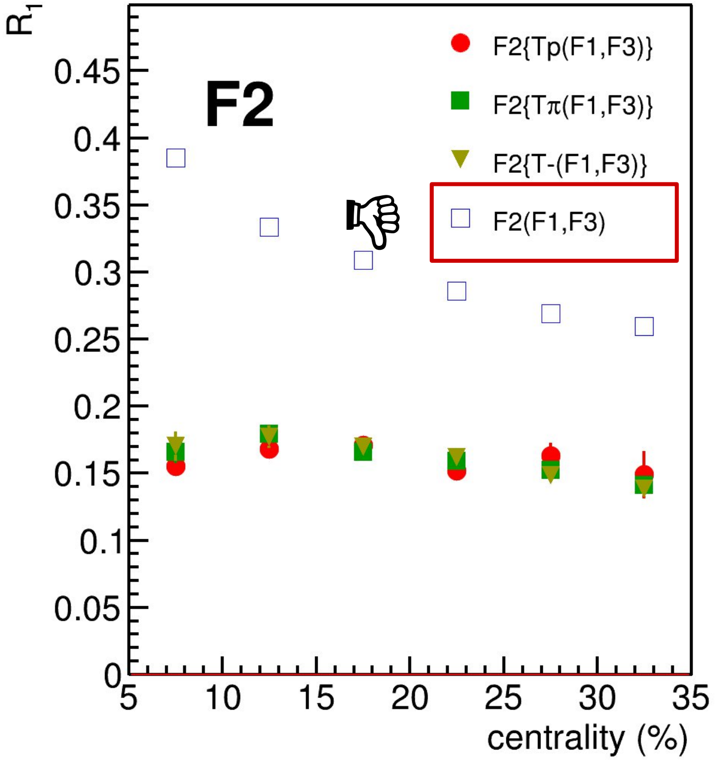
- The feasibility study for the flow measurements in the MPD experiment in a fixed-target mode was carried out with GEANT4 detector simulation and UrQMD Bi+Bi@1.45A GeV events as an input
- Acceptances of the BM@N and MPD facilities were compared:
  - MPD has greater coverage of the backward rapidities and midrapidity region
  - MPD has more uniform coverage for the azimuthal angle
- The procedure for the resolution correction factor R_1 with 3 sub-event method and rapidity-separated combinations of Q-vectors was employed
  - Two separate estimations for the R_1 for each symmetry plane were found in a good agreement
- Directed and elliptic flow for protons and light mesons were measured
  - For each particle species v_1 and v_2 are consistent with the model signal mostly in backward rapidities
- Perform flow measurements for MPD FXT for different energies: $\sqrt{s_{NN}}$=2.5, 3.0, 3.5 GeV

Thank you for your attention!

Backup

Flow methods for v_n calculation

Method helps to eliminate non-flow
Using 2-subevents doesn't work



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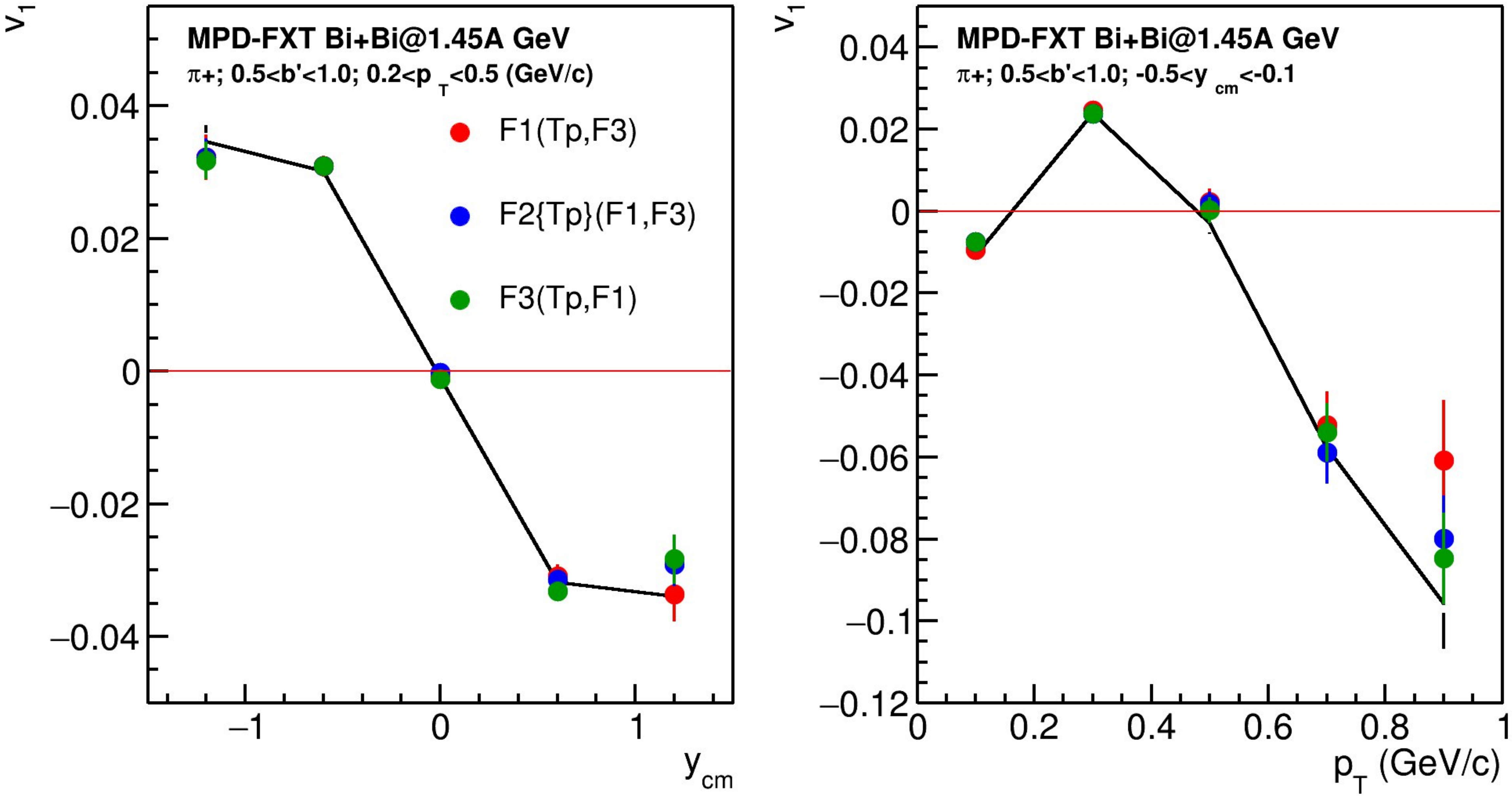
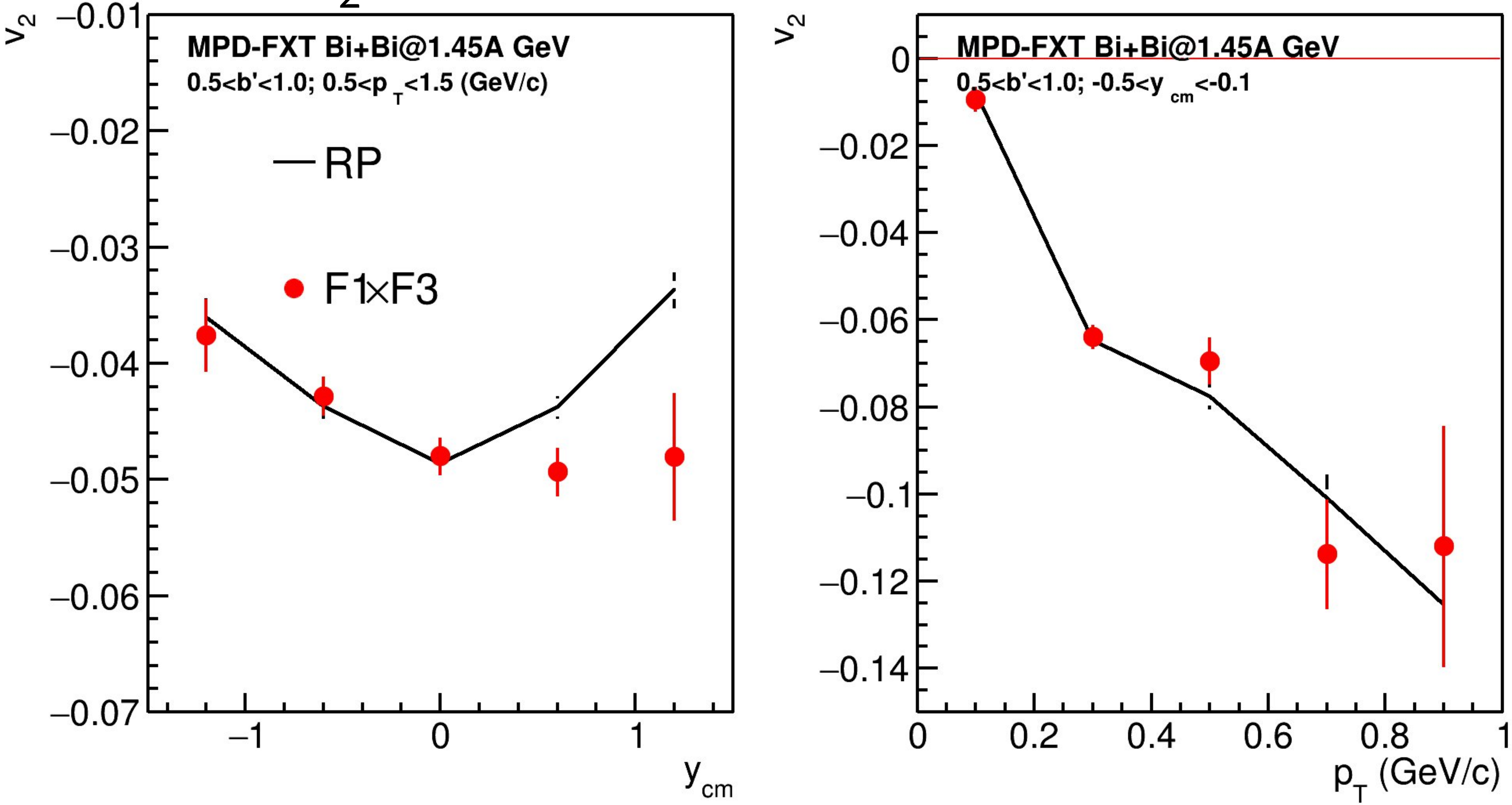
MPD-FXT: v_1 for π+



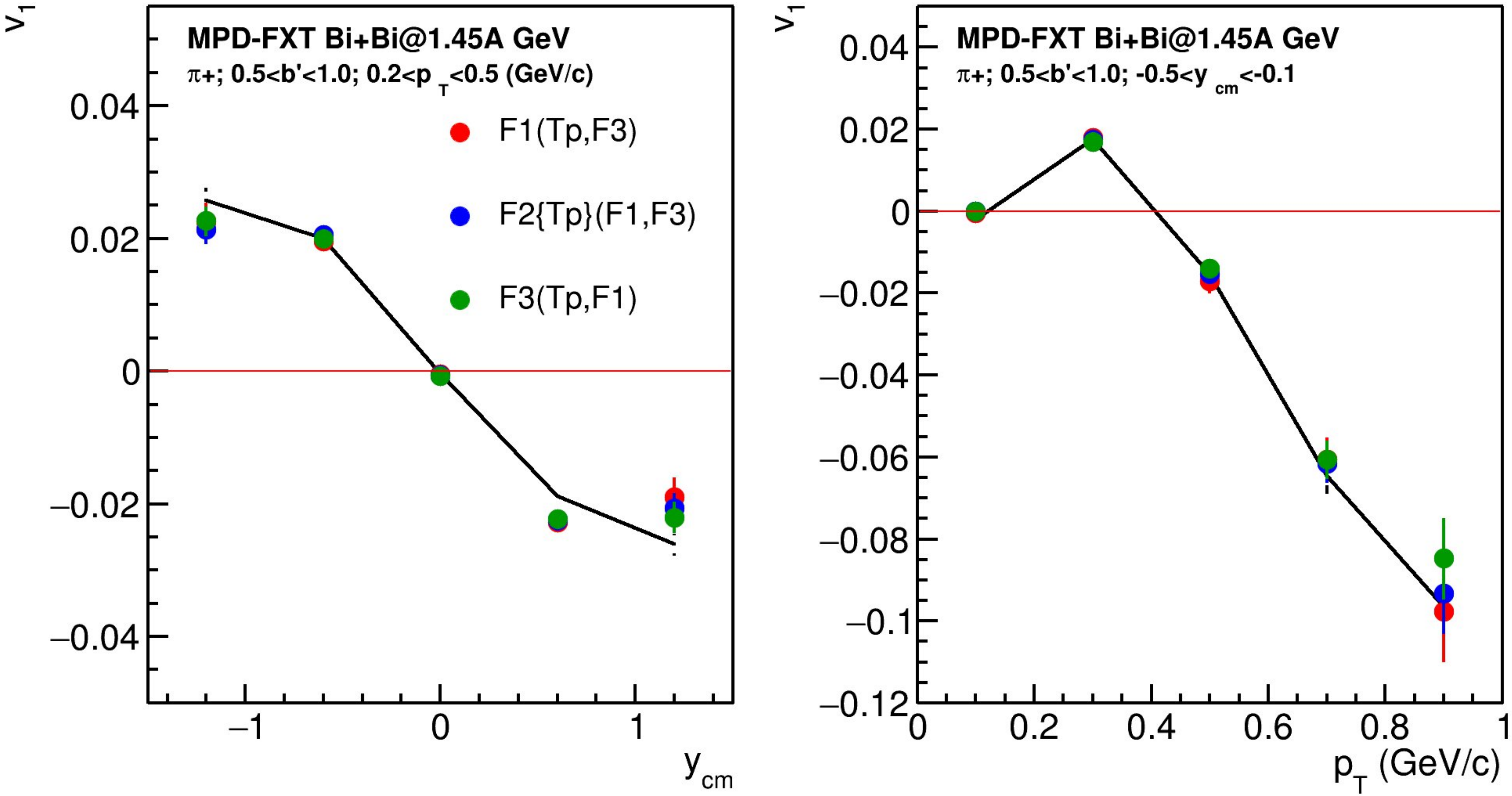
v_1 is consistent with model signal for y < 1; We need more statistics

MPD-FXT: v_2 for π+



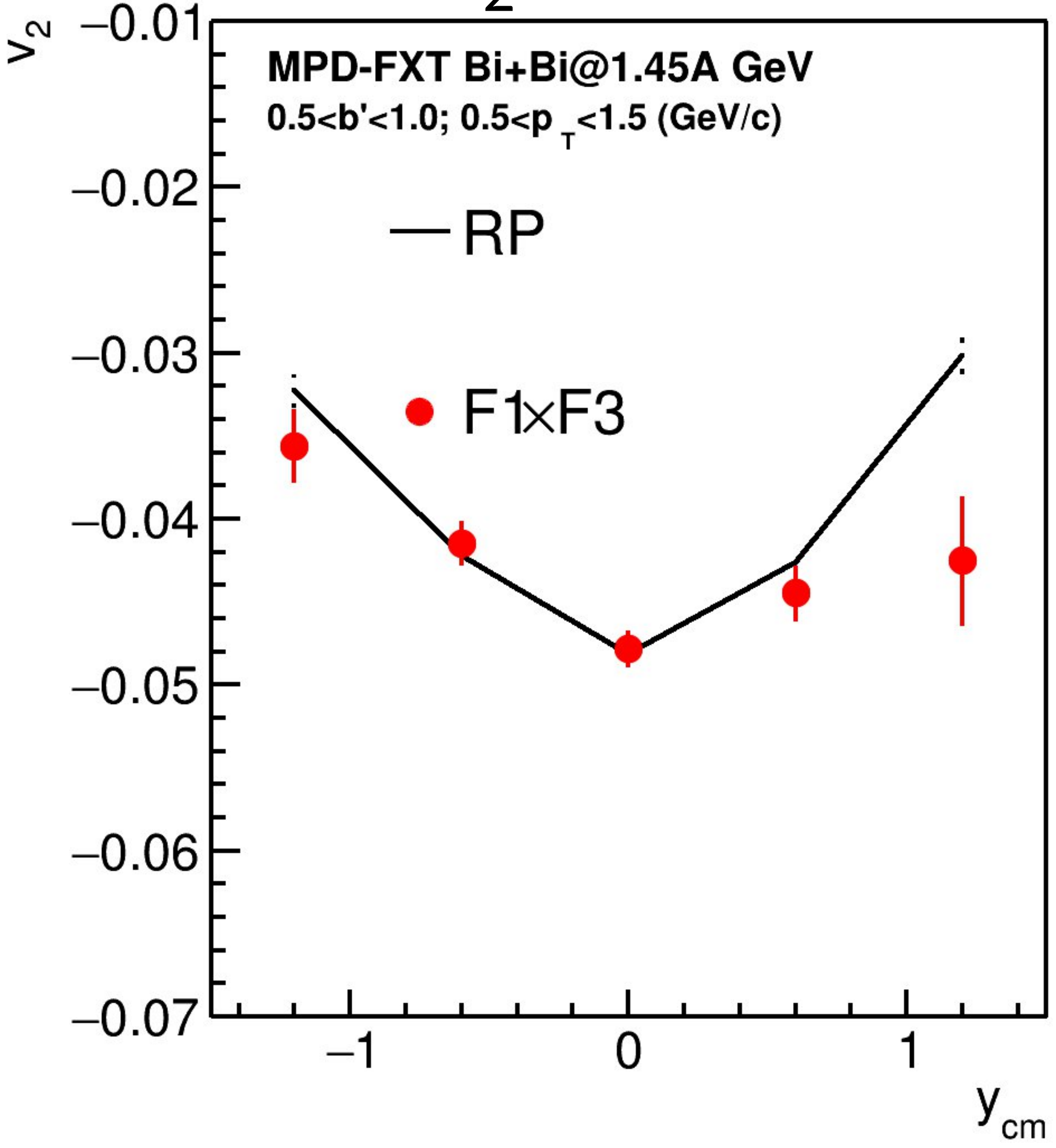
v_2 is consistent with model signal for y < 0; We need more statistics

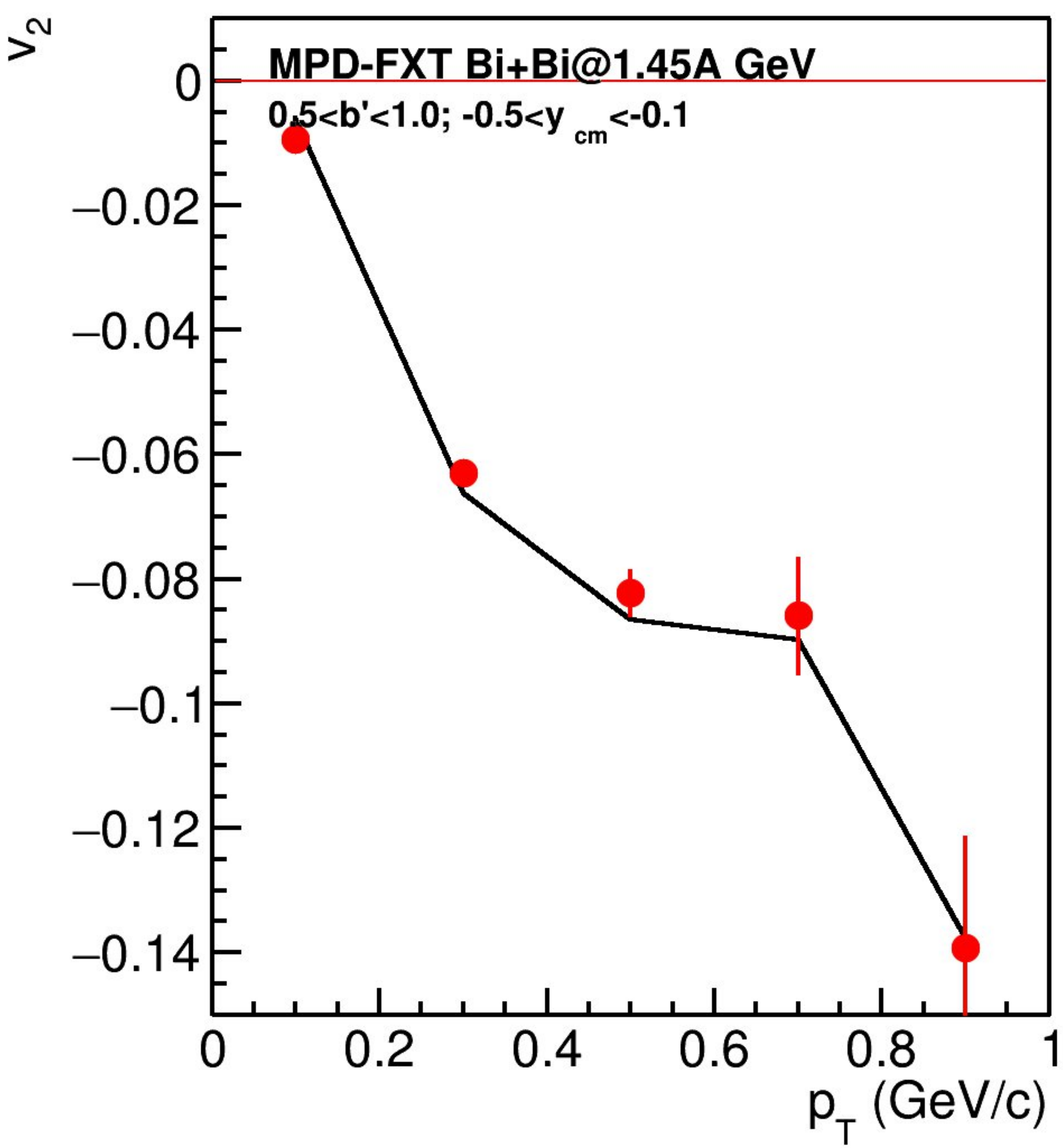
MPD-FXT: v_1 for π-



v_1 is consistent with model signal for y < 1; We need more

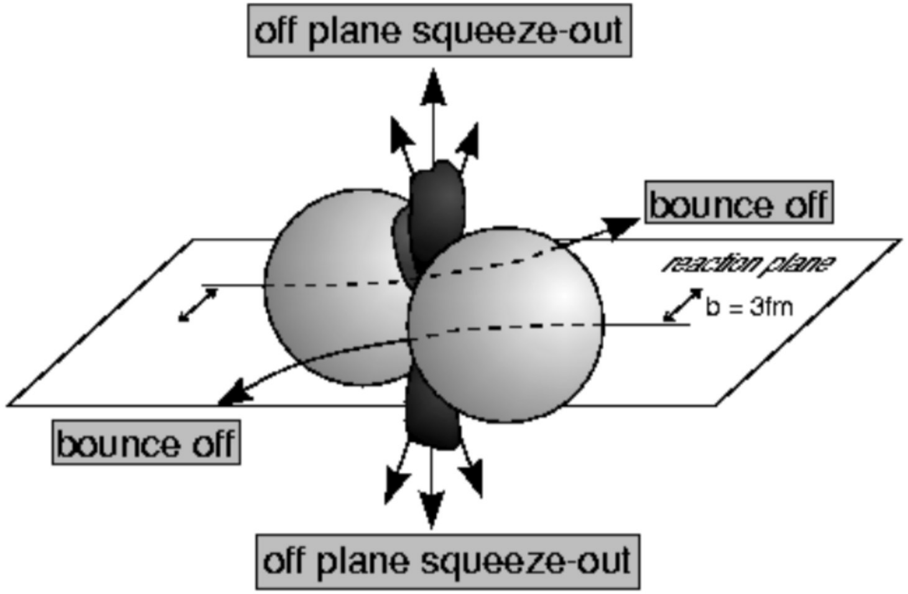
MPD-FXT: v_2 for π-





v_2 is consistent with model signal for y < 0; We need more statistics

Anisotropic flow & spectators



The azimuthal angle distribution is decomposed
in a Fourier series relative to reaction plane angle:

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

Anisotropic flow:

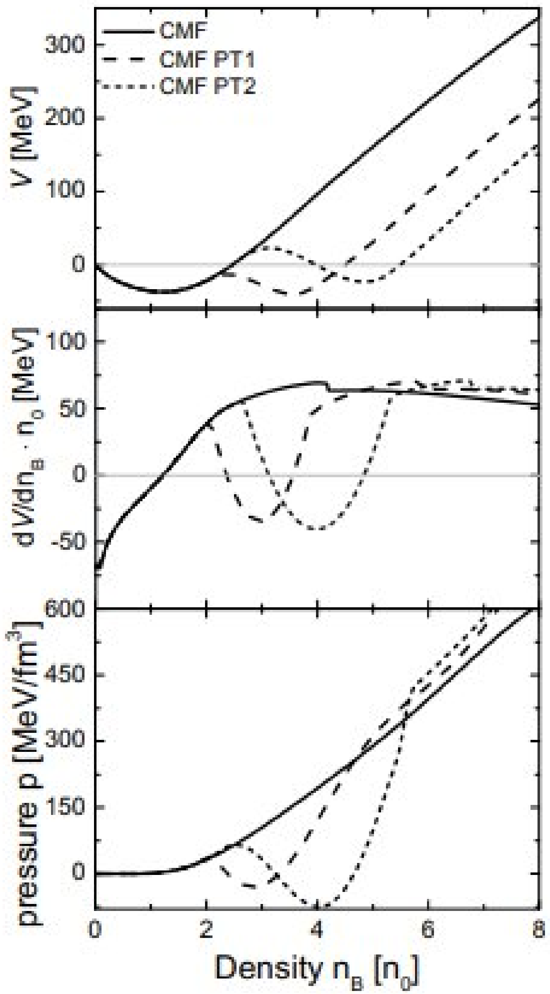
$$v_n = \langle \cos\left[n(\varphi - \Psi_{RP})\right] \rangle$$

Anisotropic flow is sensitive to:

- Time of the interaction between overlap region and spectators
- Compressibility of the created matter

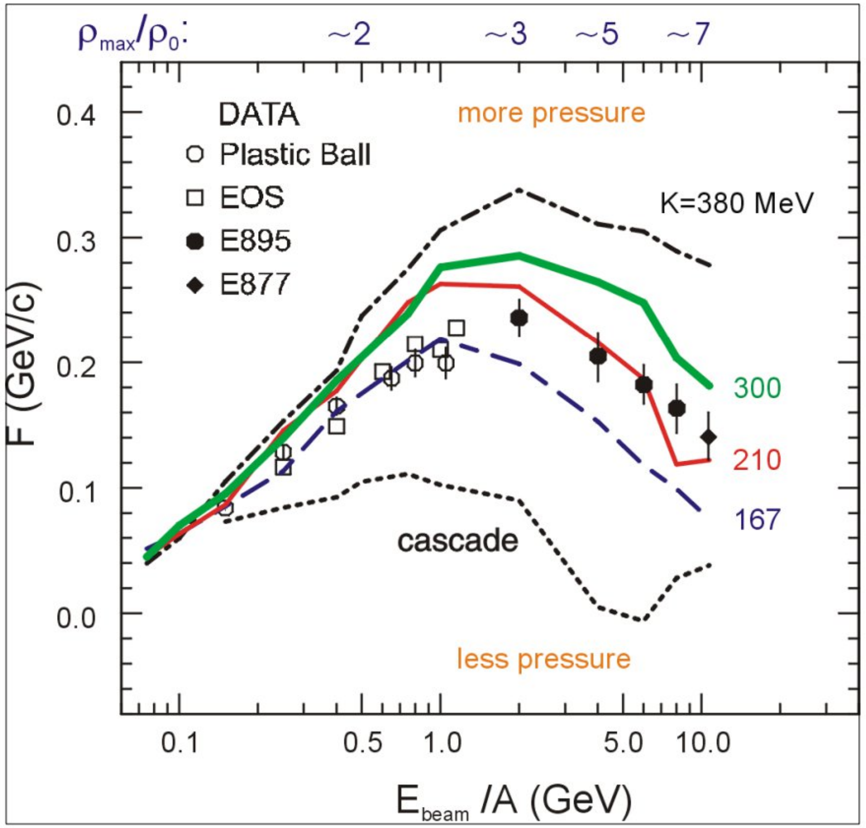
v_n as a function of collision energy

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

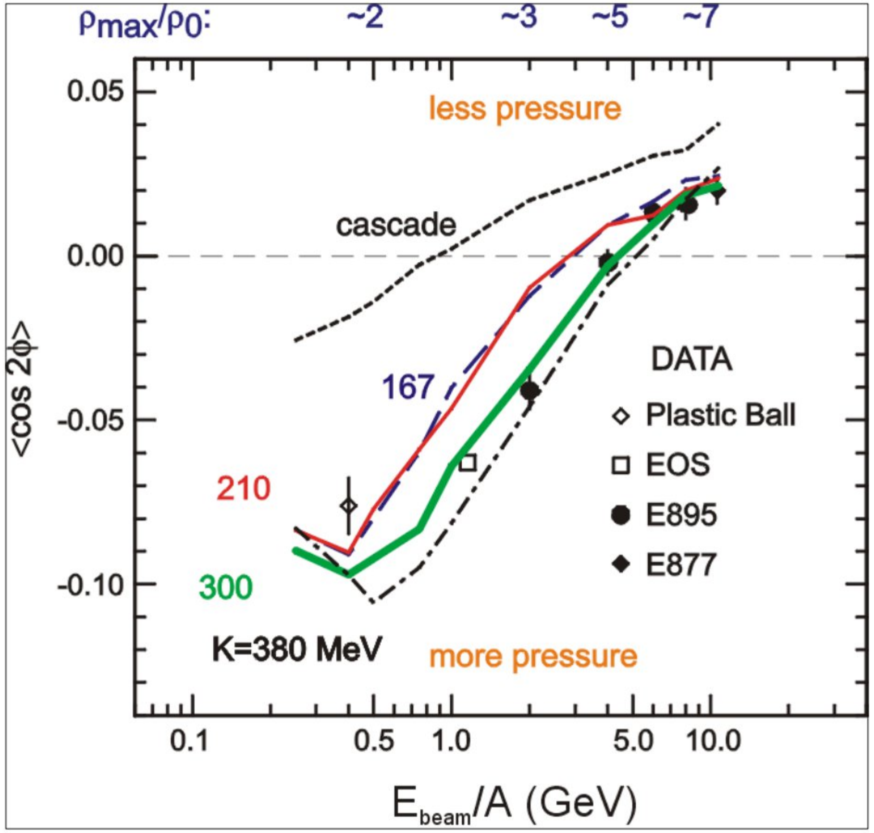


EPJ Web of Conferences 276, 01021 (2023)

v_1 suggests softer EOS



v_2 suggests harder EOS

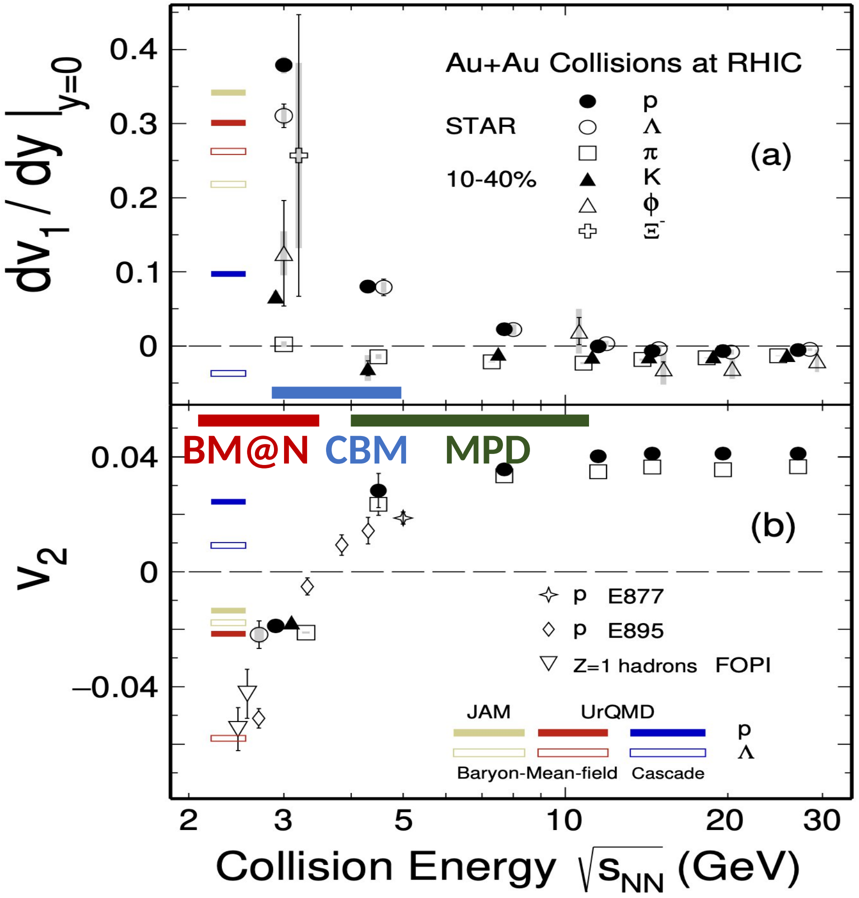


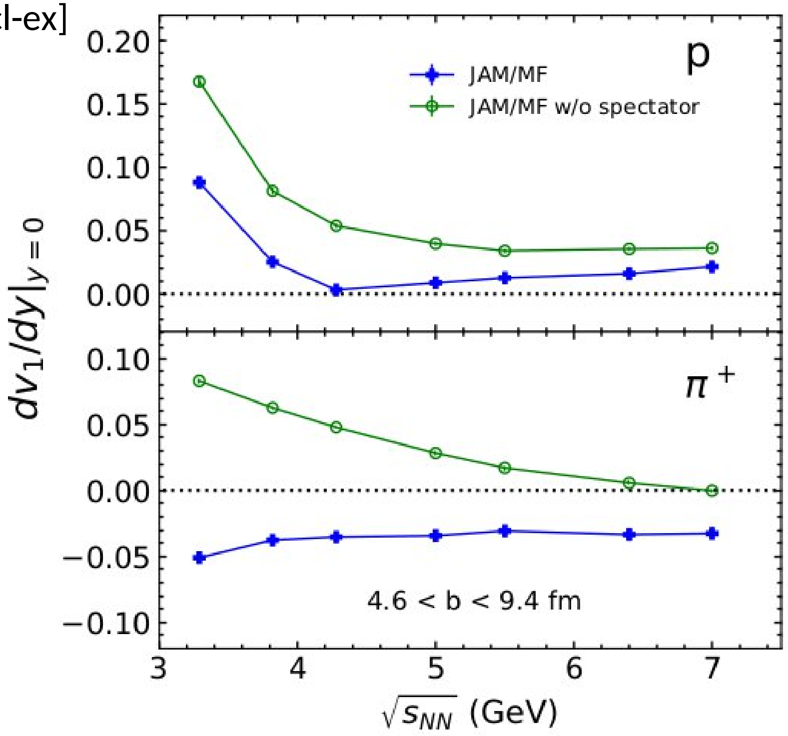
Describing the high-density matter using the mean field
Flow measurements constrain the mean field

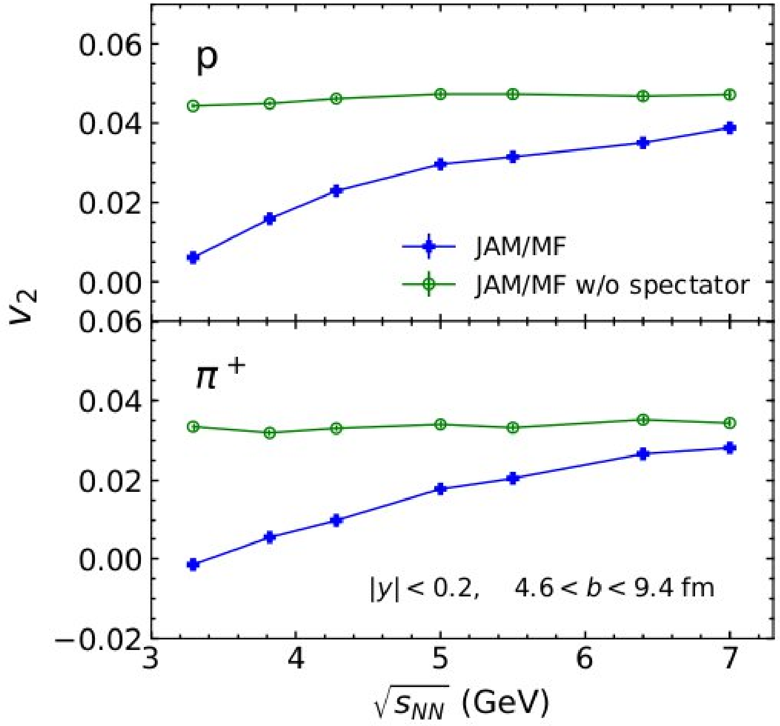
Discrepancy is probably due to non-flow correlations

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

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







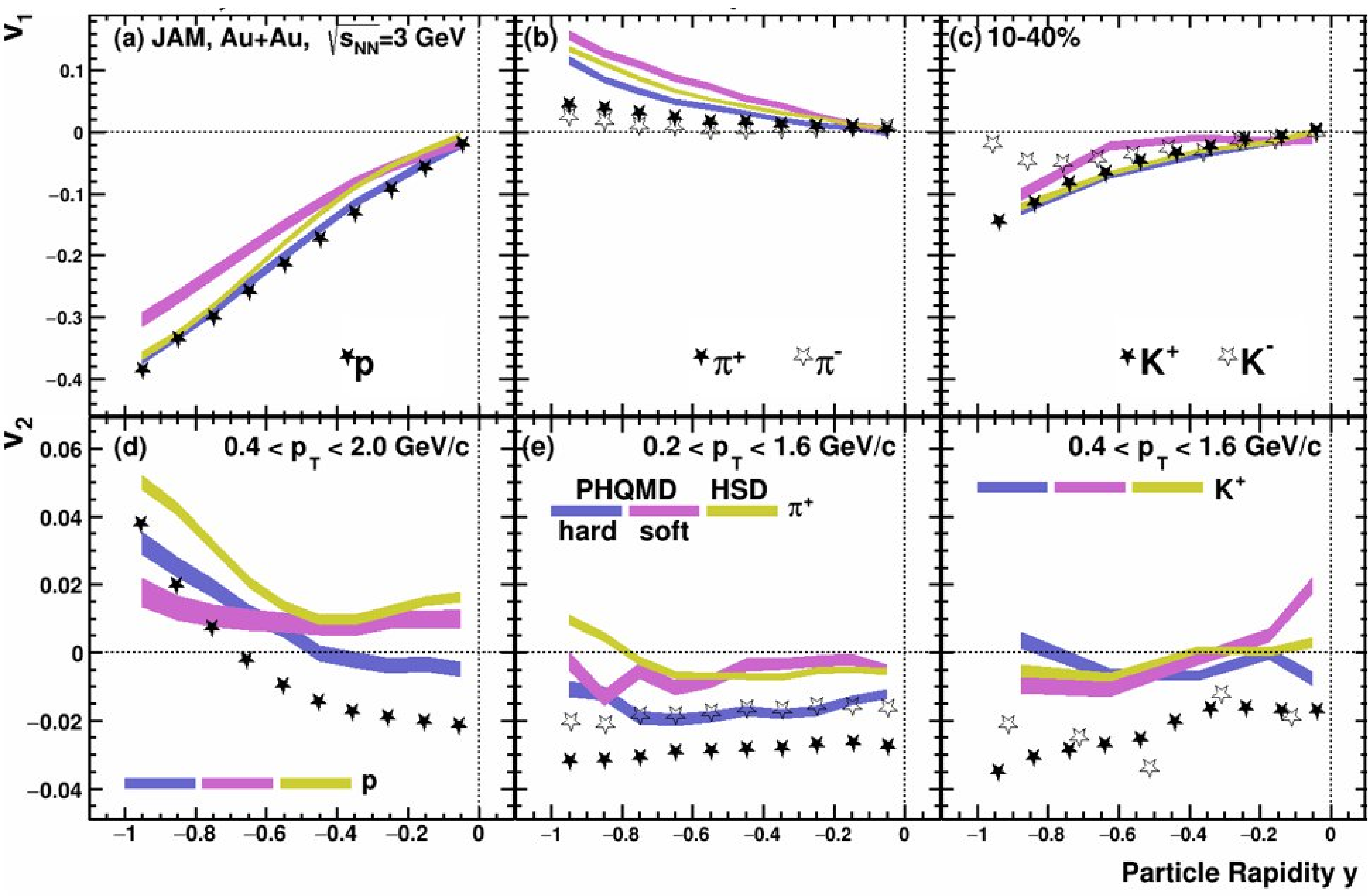
$$\frac{dN}{d\phi} \propto 1 + 2\sum_{n=1} v_n \cos[n(\phi - \Psi_{RP})], \; v_n = \langle \cos[n(\phi - \Psi_{RP})] \rangle$$

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

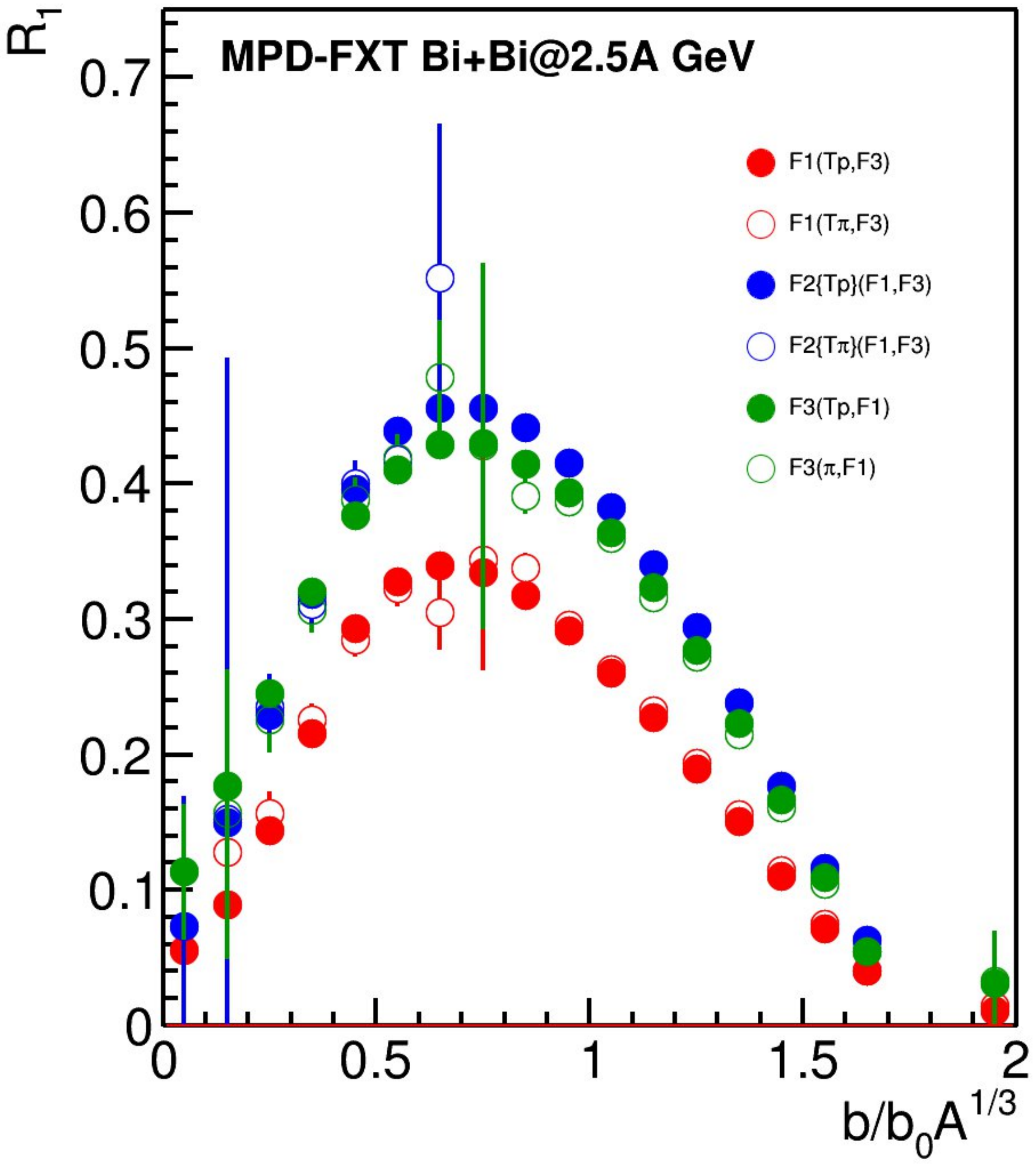
I. The ability of pressure developed early in the reaction zone ($t_{exp} = R/c_s$, $c_s = c\sqrt{dp/d\varepsilon}$) and

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

STAR-FXT vs JAM

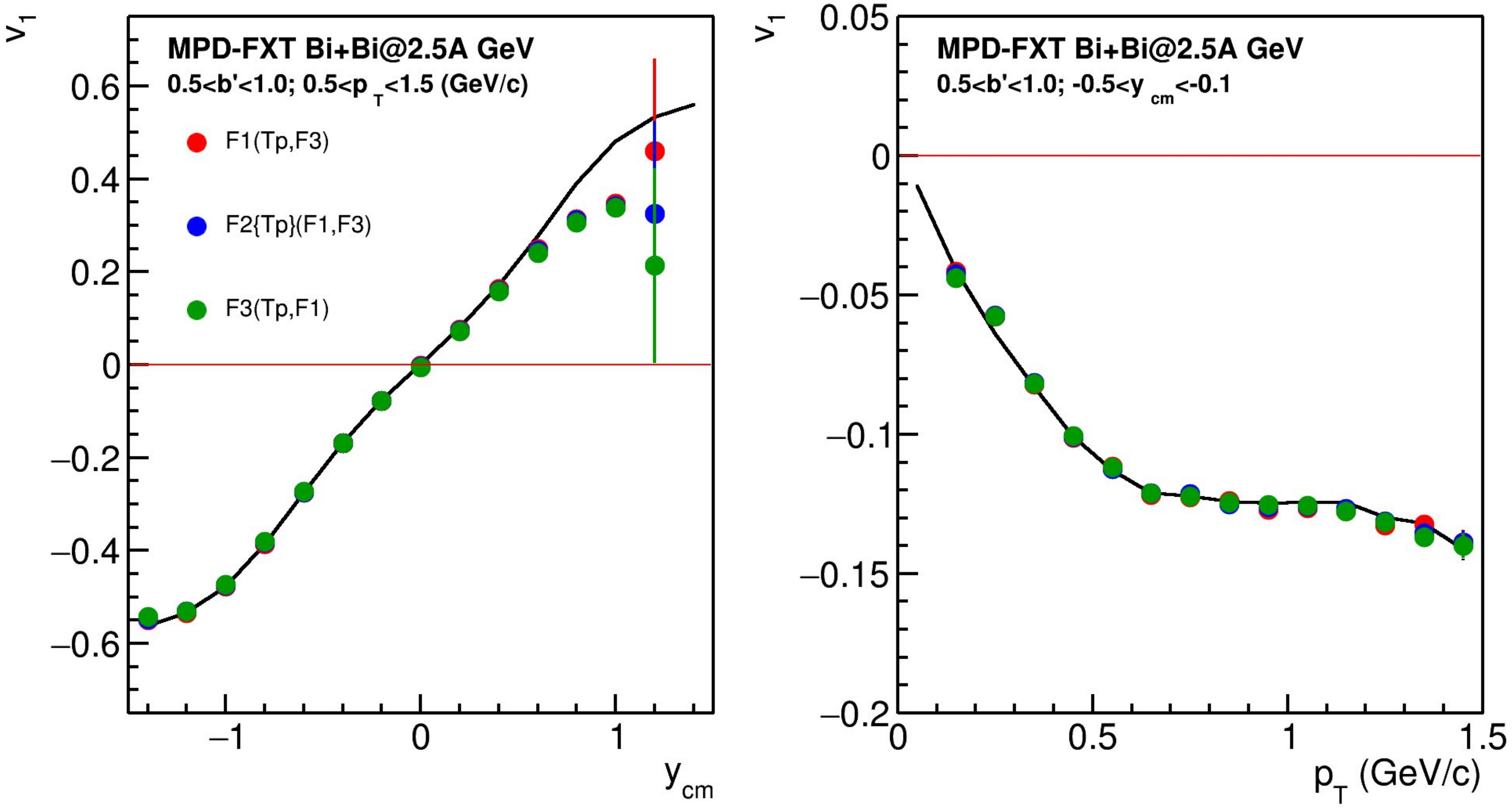


R_1 for FHCal spectator plane

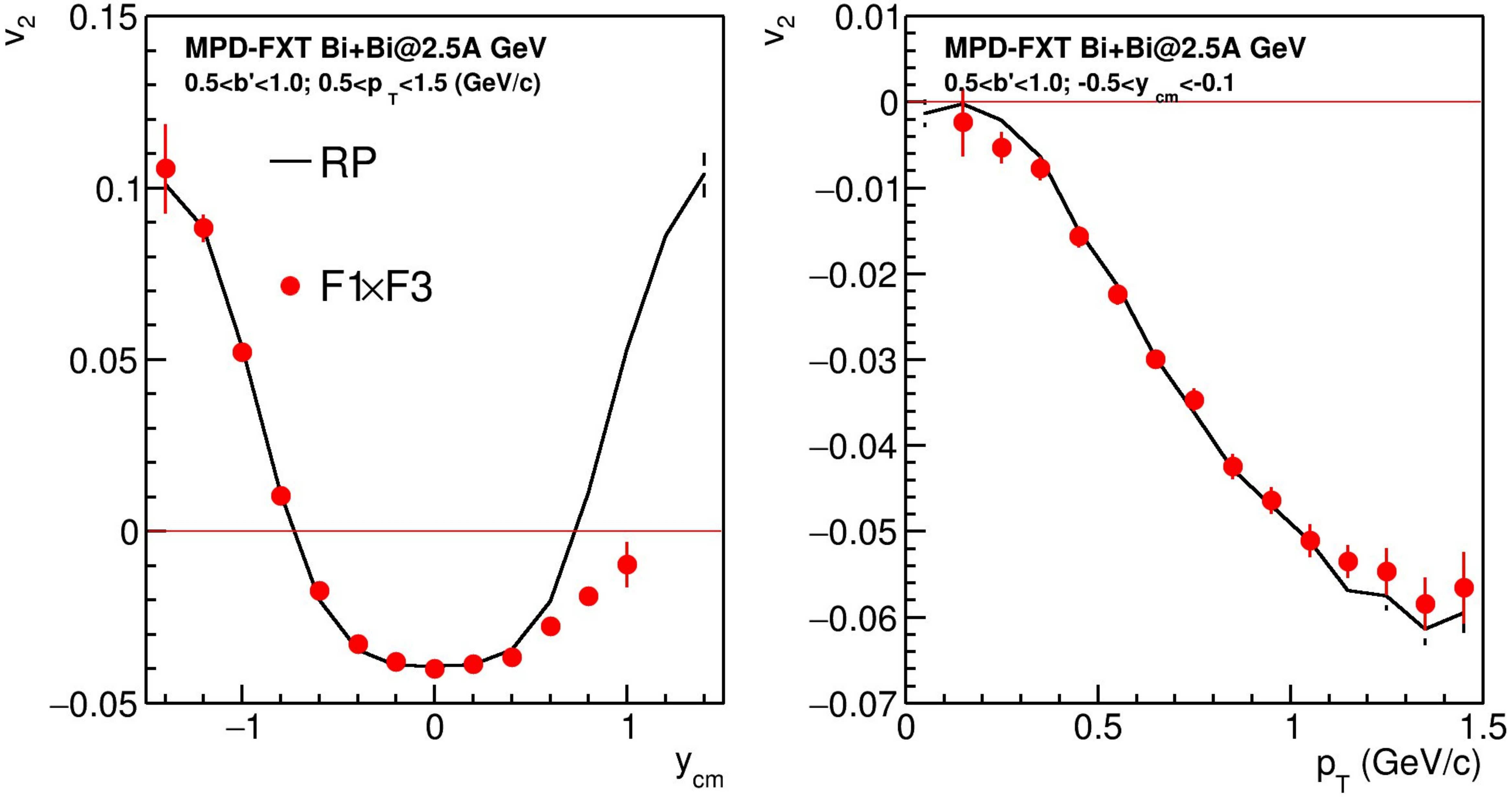


Good agreement between R_1 calculated using different combinations of Q-vectors with significant rapidity separation

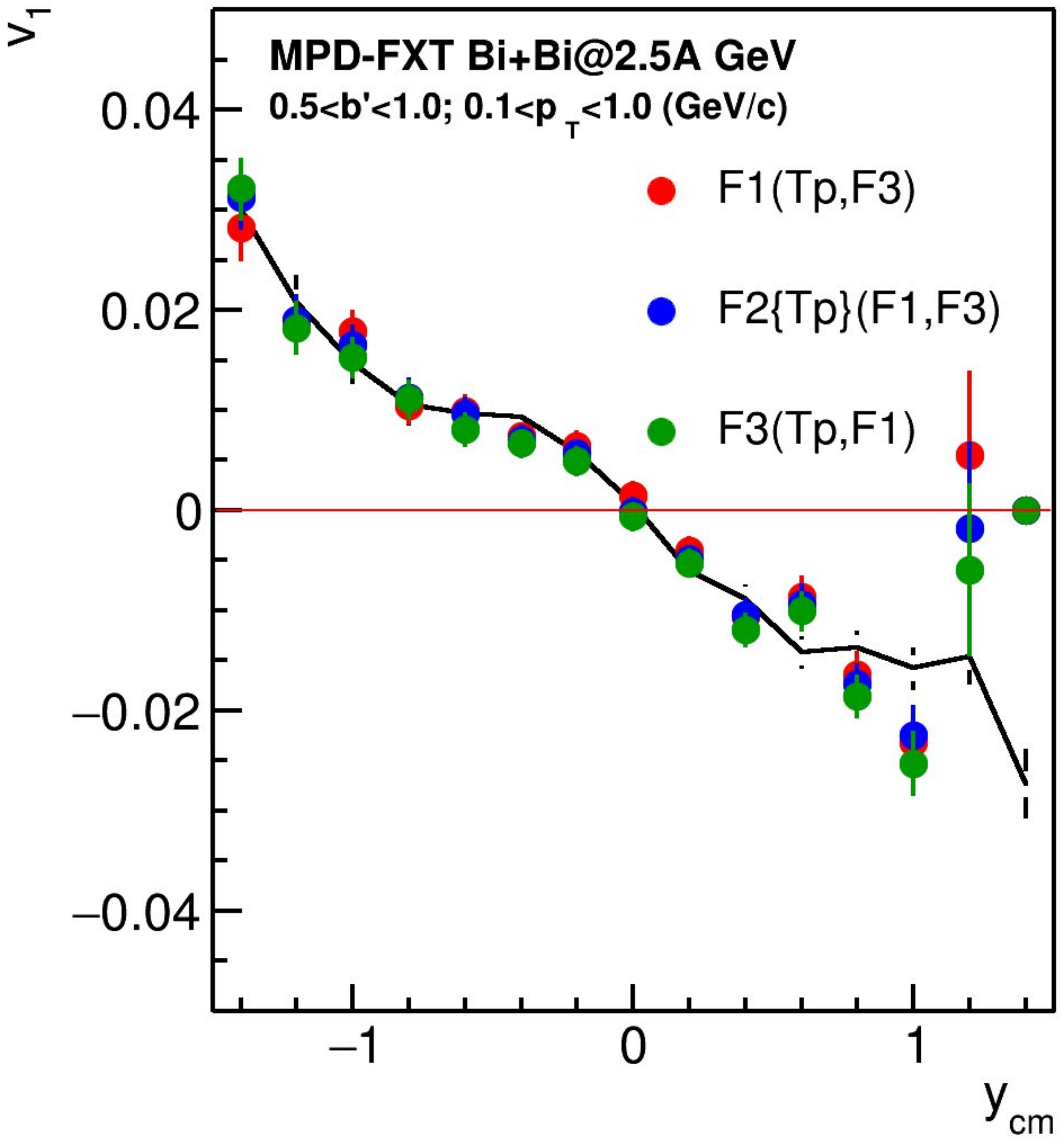
v_1 for protons



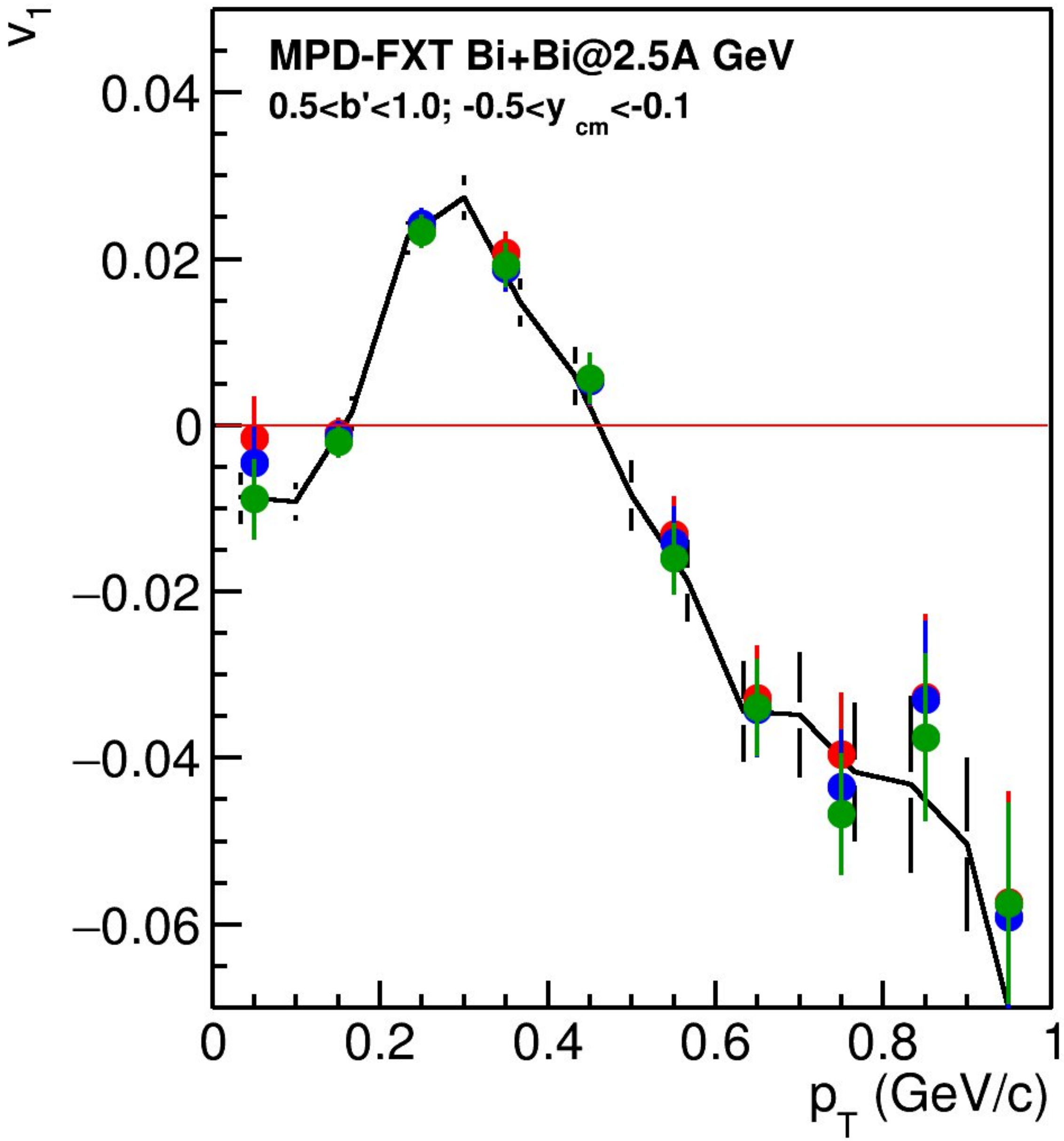
v_2 for protons



v_1 for pi+

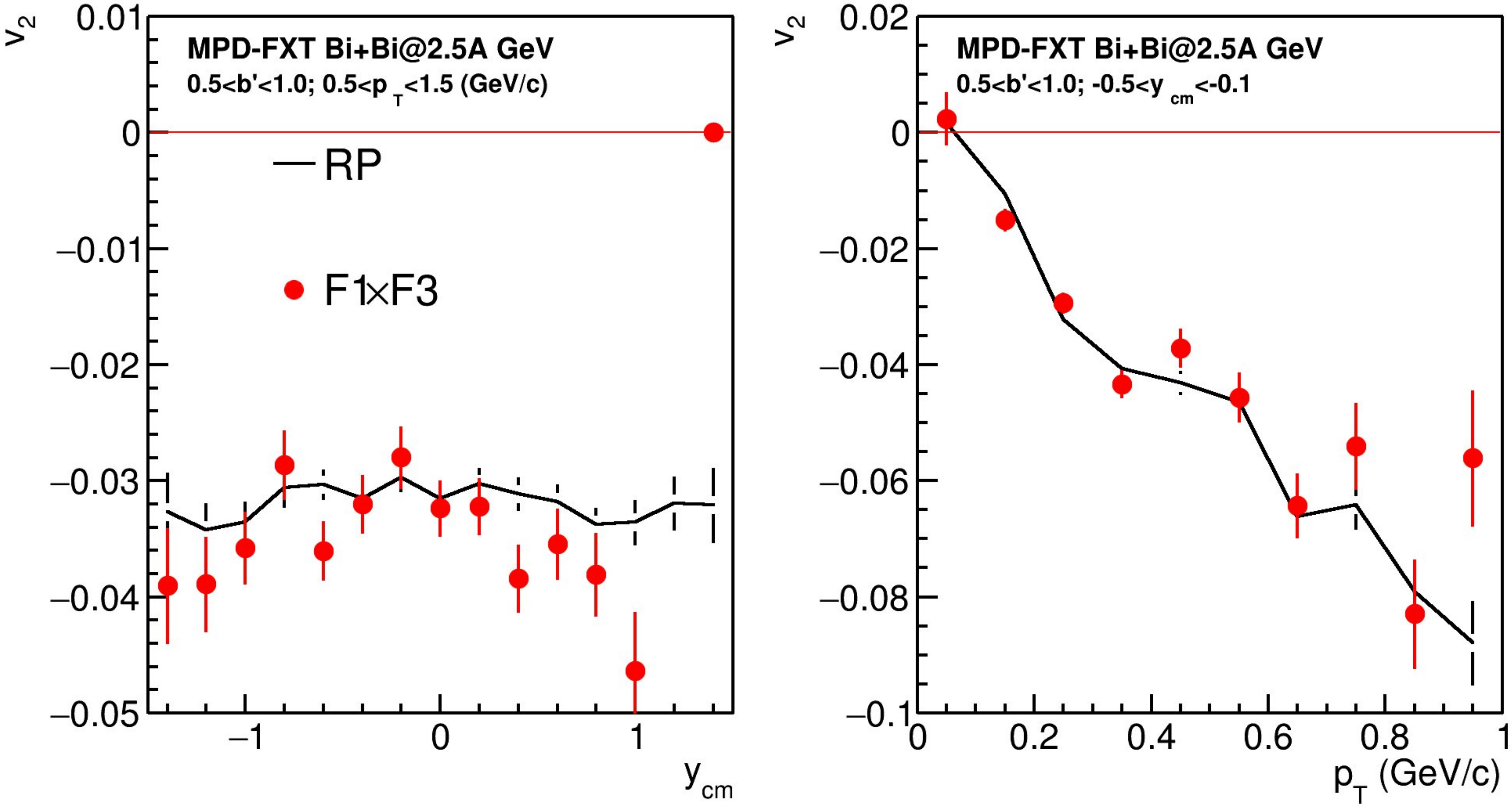


MPD-FXT Bi+Bi@2.5A GeV
0.5<b'<1.0; 0.1<p_T<1.0 (GeV/c)
F1(Tp,F3)
F2{Tp}(F1,F3)
F3(Tp,F1)
v1
ycm



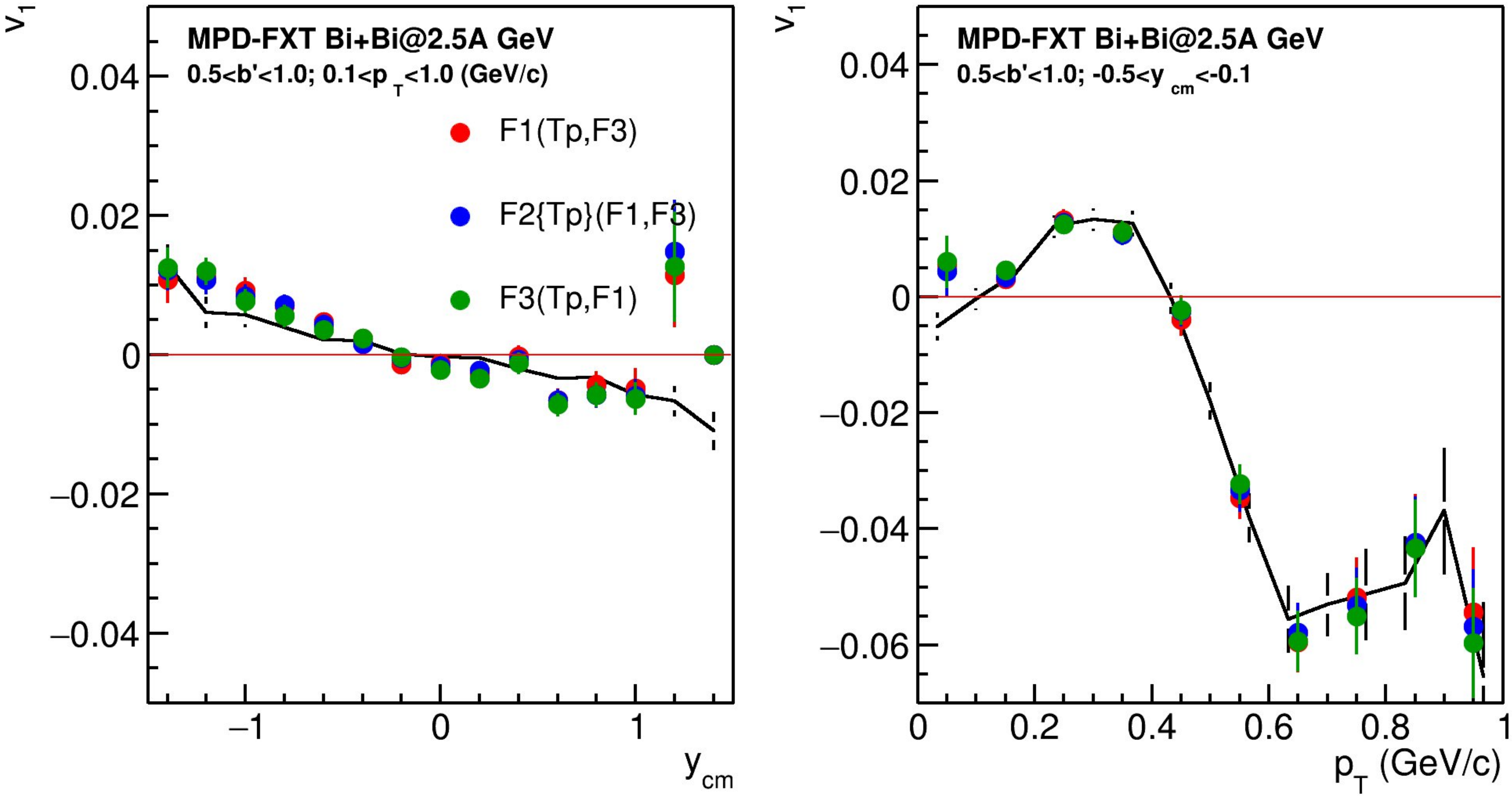
MPD-FXT Bi+Bi@2.5A GeV
0.5<b'<1.0; -0.5<y_cm<-0.1
v1
pT (GeV/c)

v_2 for pi+



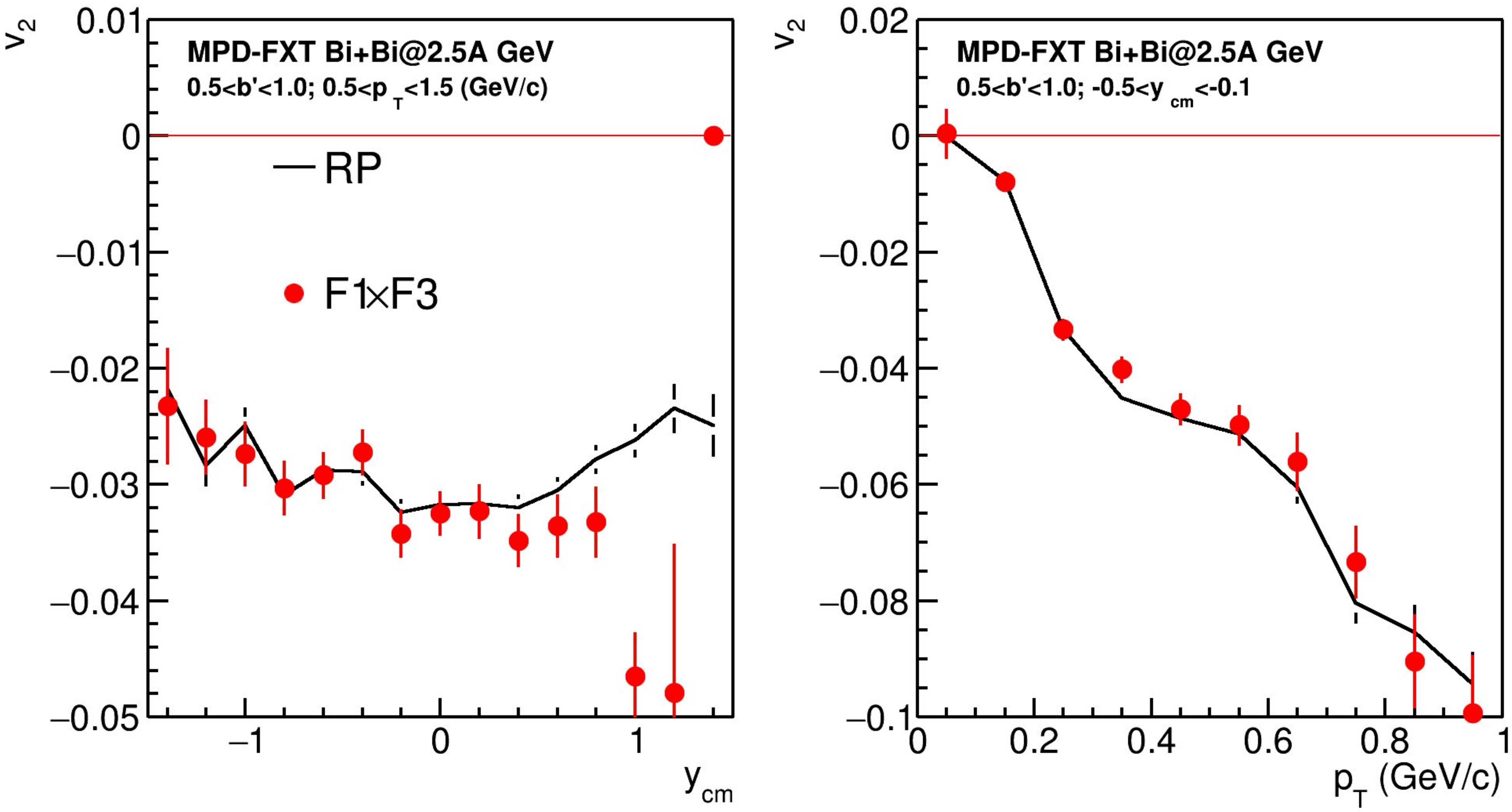
MPD-FXT Bi+Bi@2.5A GeV
0.5<b'<1.0; 0.5<p T<1.5 (GeV/c)
RP
F1×F3
v2
ycm
0.01
0
−0.01
−0.02
−0.03
−0.04
−0.05
−1
0
1
MPD-FXT Bi+Bi@2.5A GeV
0.5<b'<1.0; -0.5<y cm<-0.1
v2
pT (GeV/c)
0.02
0
−0.02
−0.04
−0.06
−0.08
−0.1
0
0.2
0.4
0.6
0.8
1

v_1 for pi-



MPD-FXT Bi+Bi@2.5A GeV
0.5<b'<1.0; 0.1<p T<1.0 (GeV/c)
F1(Tp,F3)
F2{Tp}(F1,F3)
F3(Tp,F1)
v1
ycm
0.04
0.02
0
−0.02
−0.04
−1
0
1
MPD-FXT Bi+Bi@2.5A GeV
0.5<b'<1.0; -0.5<y cm<-0.1
v1
pT (GeV/c)
0.04
0.02
0
−0.02
−0.04
−0.06
0
0.2
0.4
0.6
0.8
1

v_2 for pi-



MPD-FXT Bi+Bi@2.5A GeV
0.5<b'<1.0; 0.5<p T<1.5 (GeV/c)
RP
F1×F3
v2
ycm
MPD-FXT Bi+Bi@2.5A GeV
0.5<b'<1.0; -0.5<y cm<-0.1
v2
pT (GeV/c)