

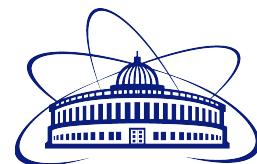
# The first results for directed flow of protons in Xe+Cs collisions at $E_{\text{kin}}=3.8A$ GeV in the BM@N experiment

Mikhail Mamaev (JINR, MEPHI)  
for the BM@N collaboration

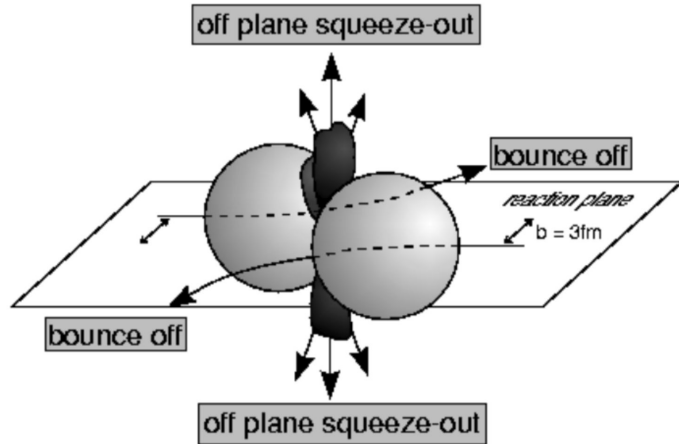
The work has been supported by the Ministry of Science and Higher Education of the Russian Federation, Project "Fundamental and applied research at the NICA megascience experimental complex" № FSWU-2024-0024



The 7th international conference on particle physics and astrophysics  
22-25 October 2024



# 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:

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

Anisotropic flow is sensitive to:

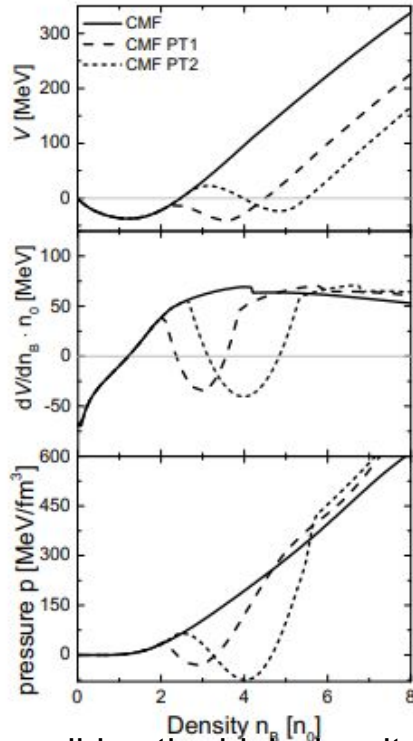
- Time of the interaction between overlap region and spectators
- Compressibility of the created matter

# $v_n$ as a function of collision energy

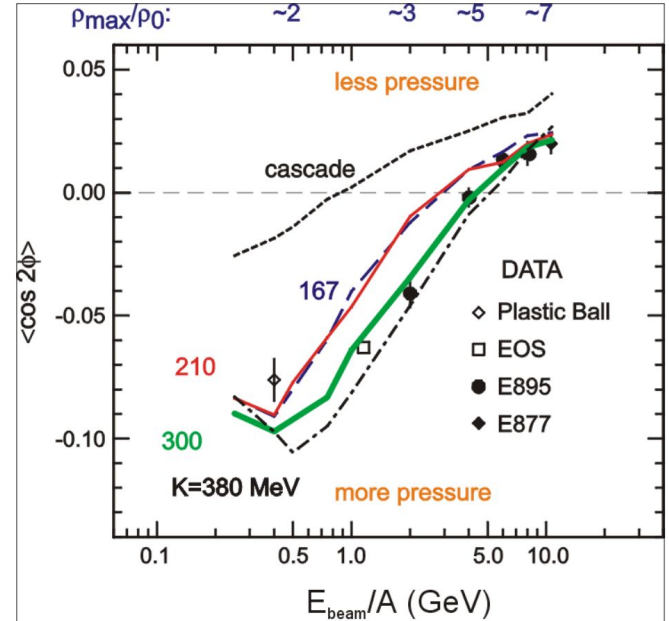
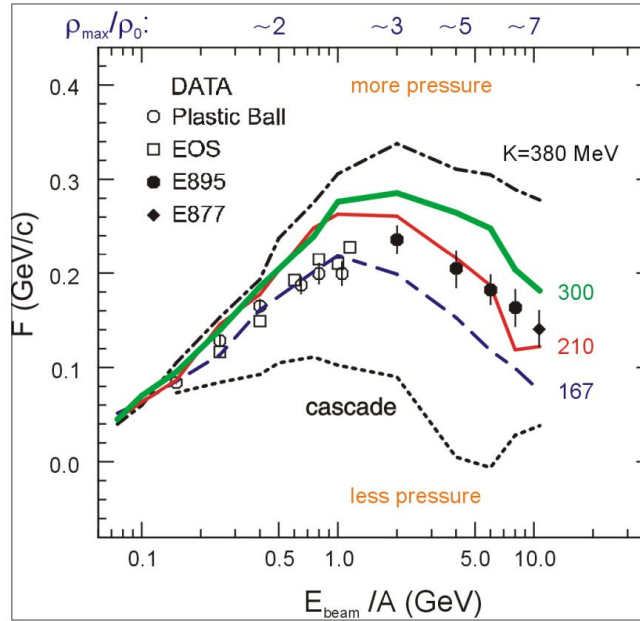
P. DANIELEWICZ, R. LACEY, W. LYNCH  
[10.1126/science.1078070](https://doi.org/10.1126/science.1078070)

$v_1$  suggests softer EOS

$v_2$  suggests harder EOS



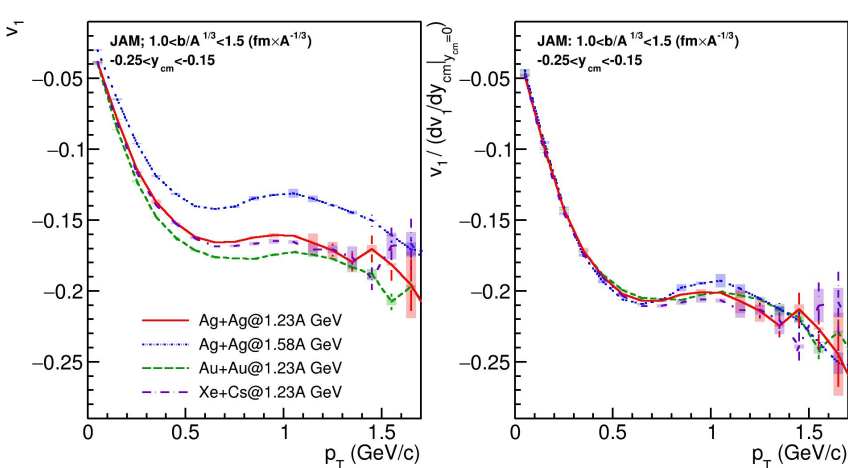
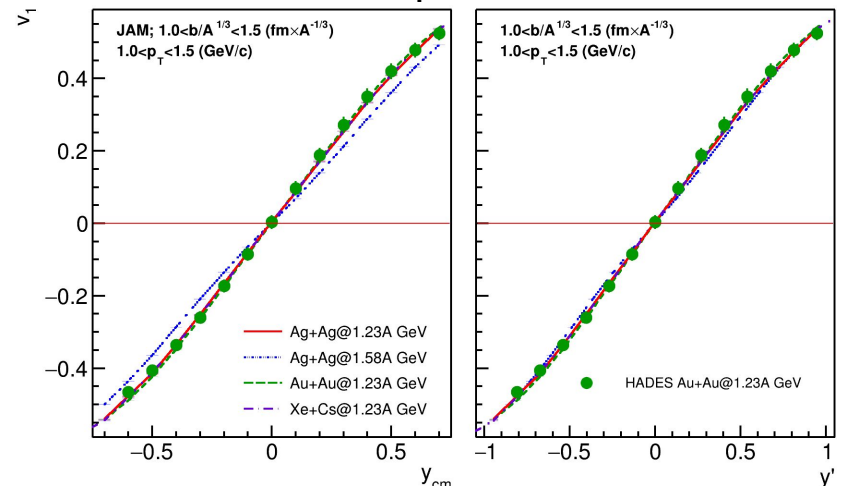
EPJ Web of Conferences 276, 01021 (2023)



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

Discrepancy is probably due to non-flow correlations

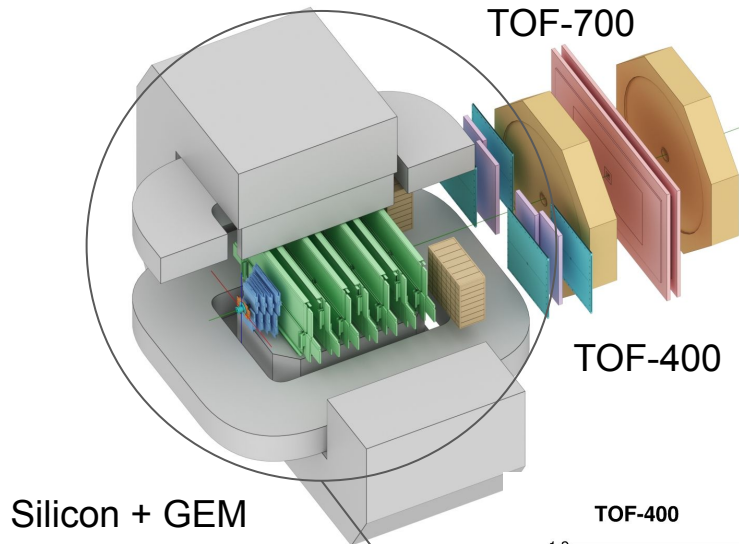
# HADES: $dv_1/dy$ scaling with collision energy and system size



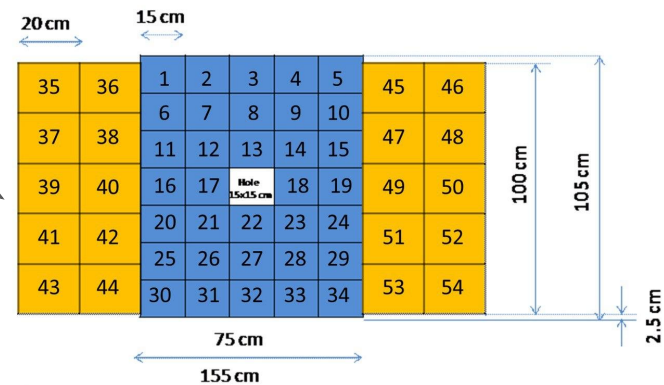
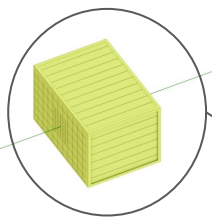
- Scaling with collision energy is observed in model and experimental data
- Scaling with system size is observed in model and experimental data
- We can compare the results with HIC-data from other experiments (e.g. STAR-FXT Au+Au)



# The BM@N experiment

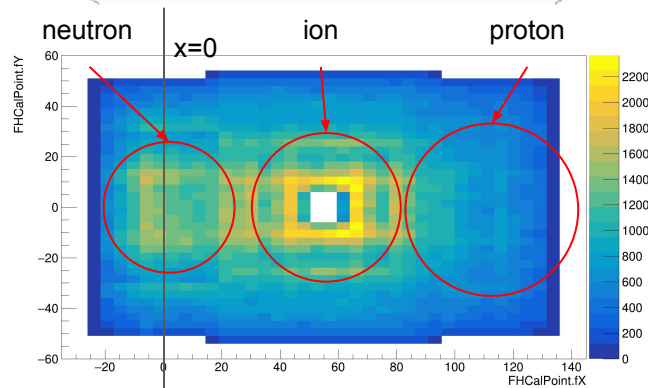
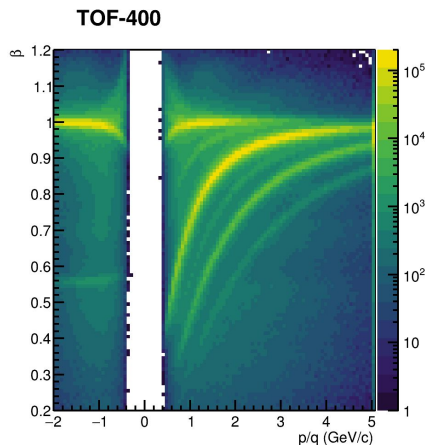


FHCaI



Silicon + GEM

High momentum and time resolution allow to identify particles



Symmetry plane estimation with the azimuthal asymmetry of projectile spector energy

# Flow vectors

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

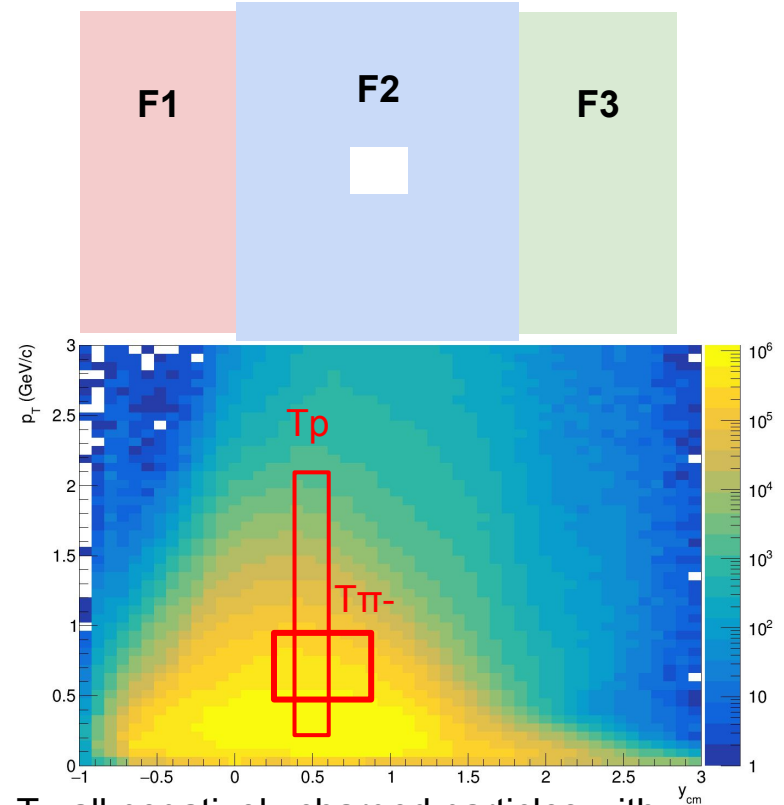
$$u_n = e^{in\phi}$$

where  $\phi$  is the azimuthal angle

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

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

$\Psi_n^{EP}$  is the event plane angle



T-: all negatively charged particles with:

- $1.5 < \eta < 4$
- $p_T > 0.2 \text{ GeV/c}$

T+: all positively charged particles with:

- $2.0 < \eta < 3$
- $p_T > 0.2 \text{ GeV/c}$

# Flow methods for $v_n$ calculation

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:

$$v_1 = \frac{\langle u_1 Q_1^{F1} \rangle}{R_1^{F1}} \quad v_2 = \frac{\langle u_2 Q_1^{F1} Q_1^{F3} \rangle}{R_1^{F1} R_1^{F3}}$$

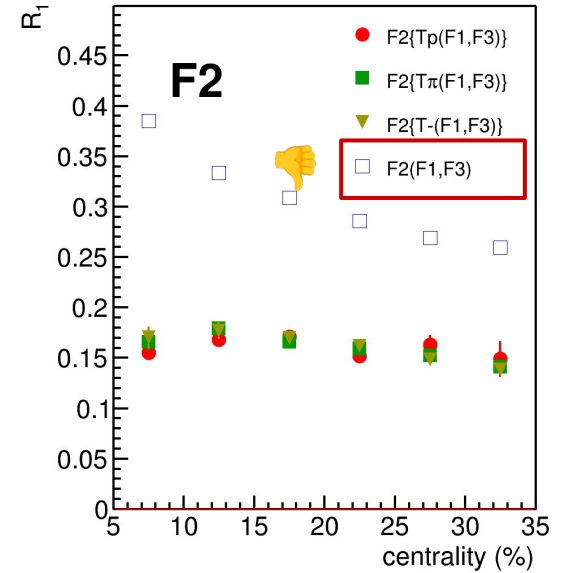
Where  $R_1$  is the resolution correction factor

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

Symbol “F2(F1,F3)” means  $R_1$  calculated via  
 (3S resolution):

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

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

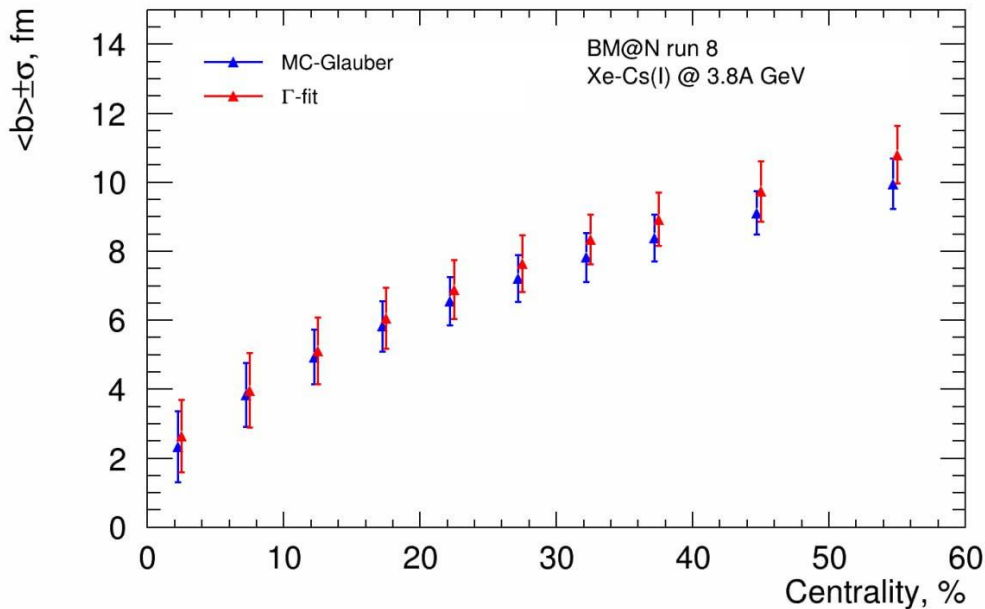


Symbol “F2{Tp}(F1,F3)” means  $R_1$   
 calculated via (4S resolution):

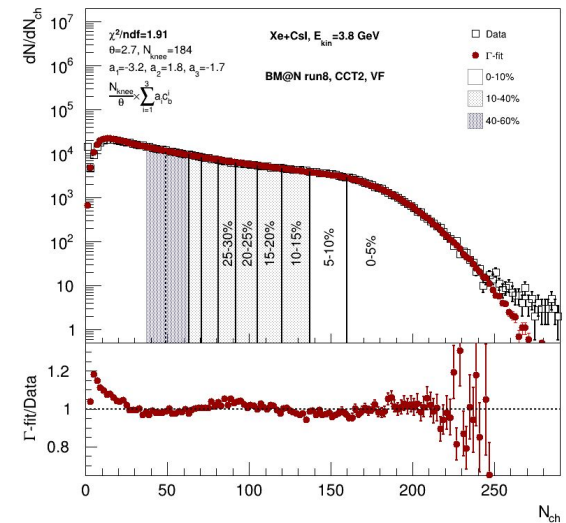
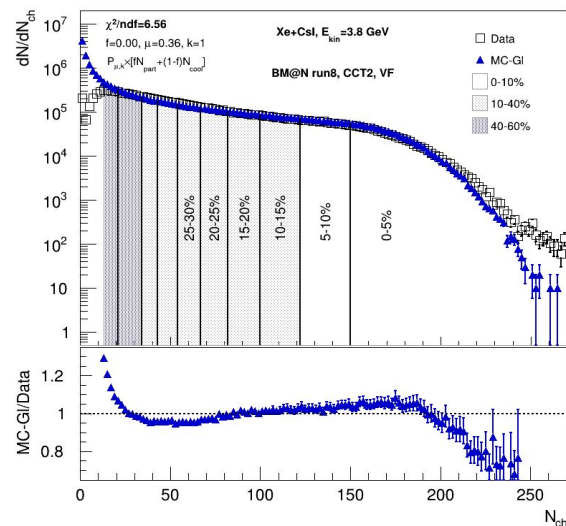
$$R_1^{F2\{Tp\}(F1,F3)} = \langle Q_1^{F2} Q_1^{Tp} \rangle \frac{\sqrt{\langle Q_1^{F1} Q_1^{F3} \rangle}}{\sqrt{\langle Q_1^{Tp} Q_1^{F1} \rangle \langle Q_1^{Tp} Q_1^{F3} \rangle}}$$

# Centrality determination methods

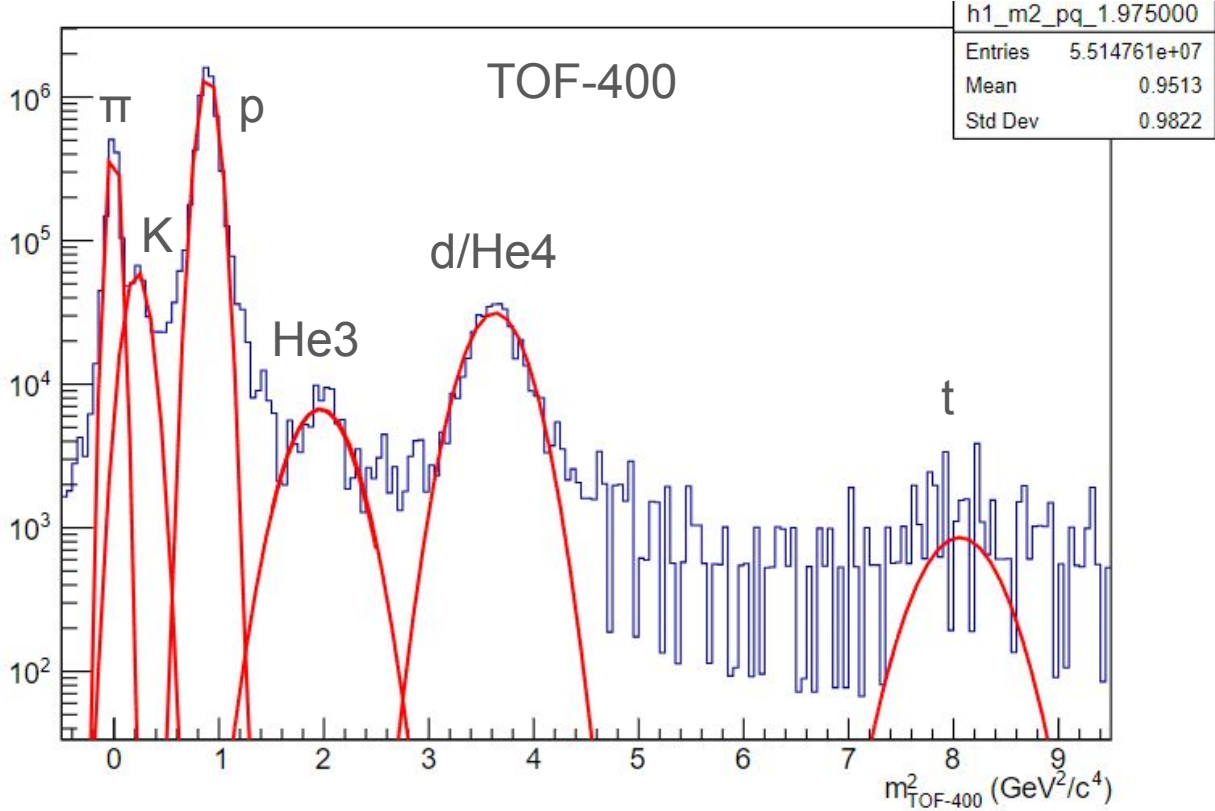
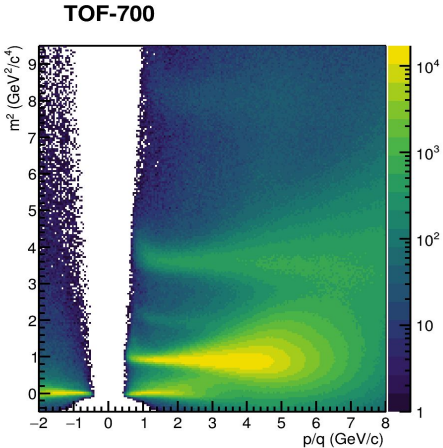
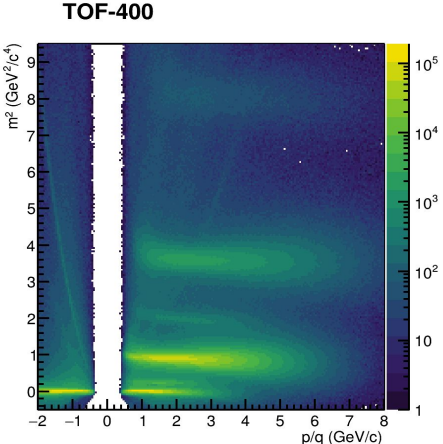
Physics of Atomic Nuclei, 2024, Vol. 87, No. 1, pp. 389–394



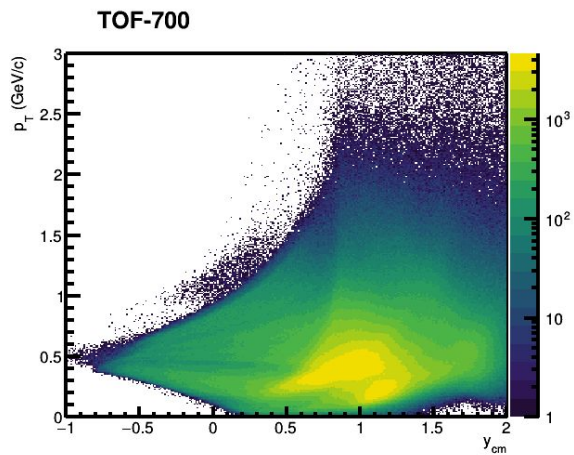
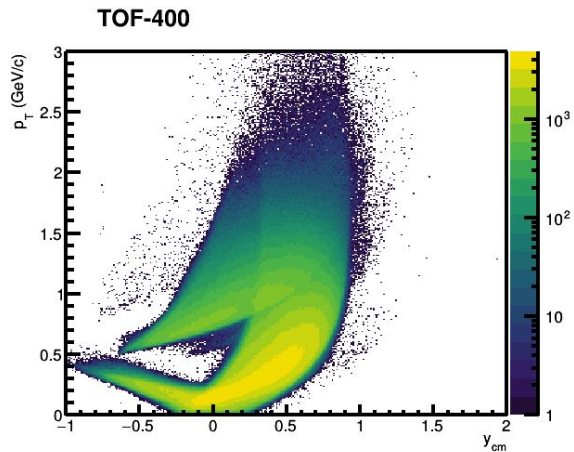
Two methods for centrality determination: MC-Glauber and  $\Gamma$ -fit method are in a good agreement



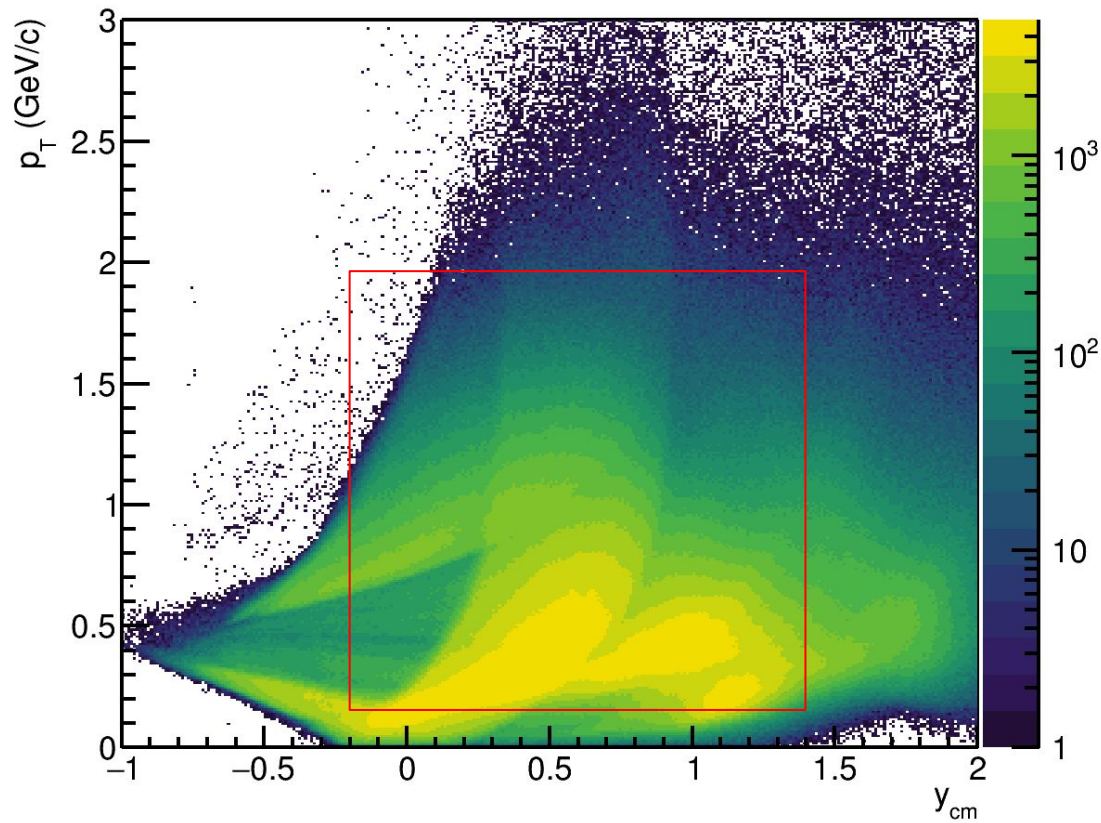
# Particle identification





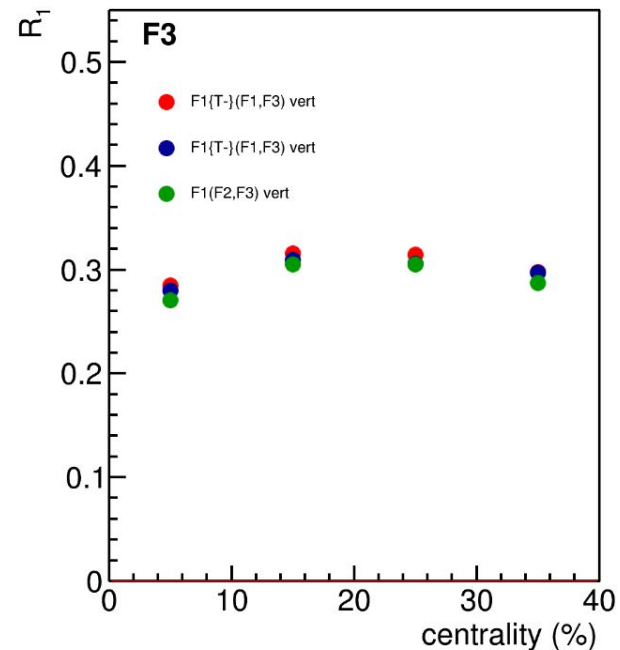
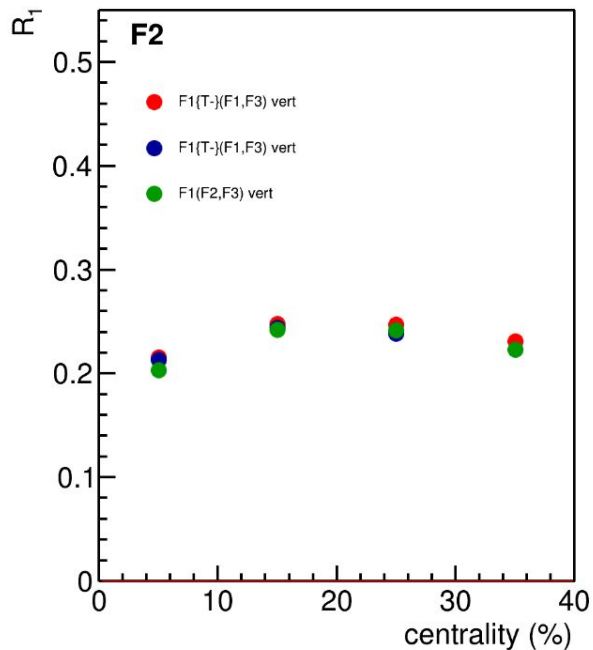
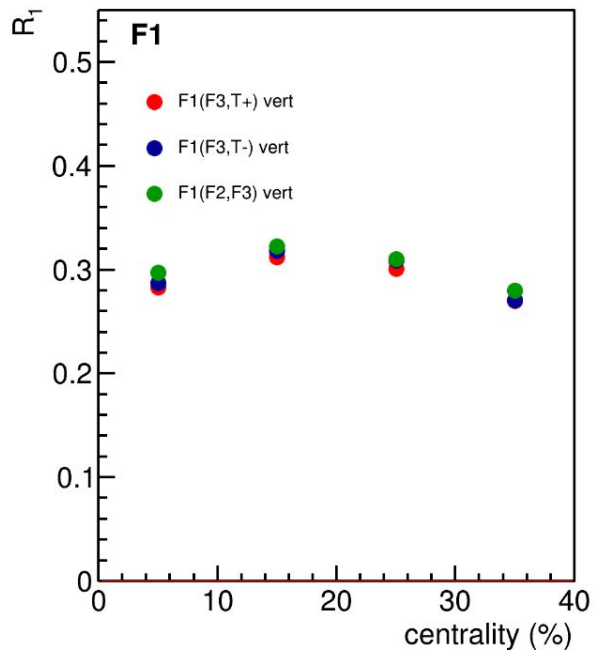
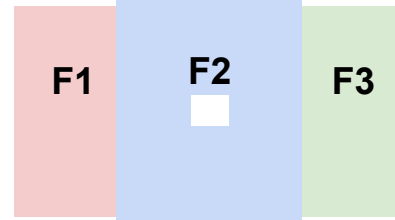


# Combined Proton $p_T$ - $y$ acceptance



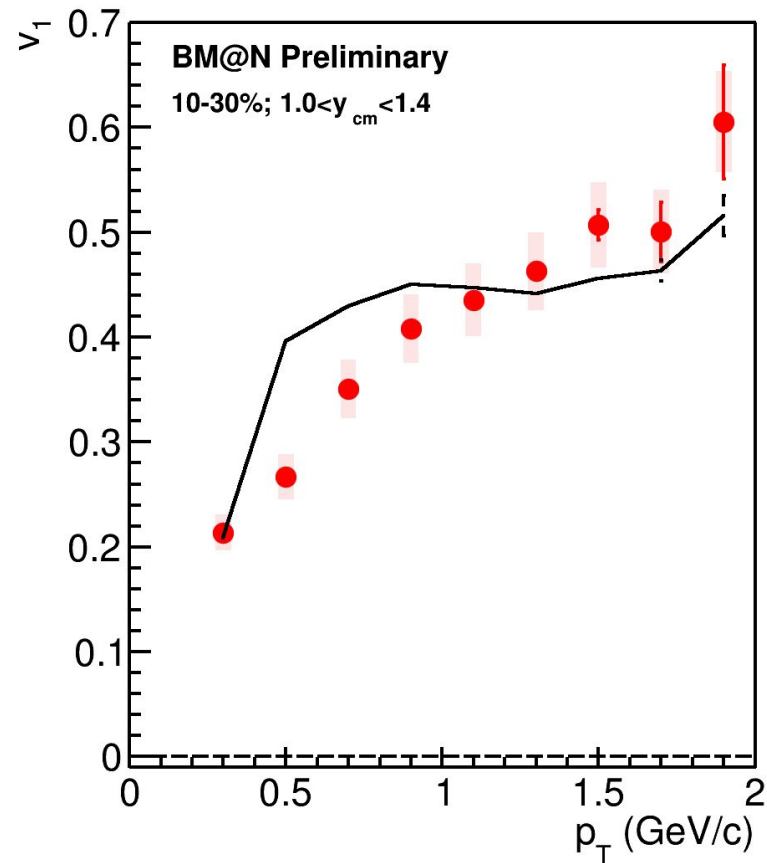
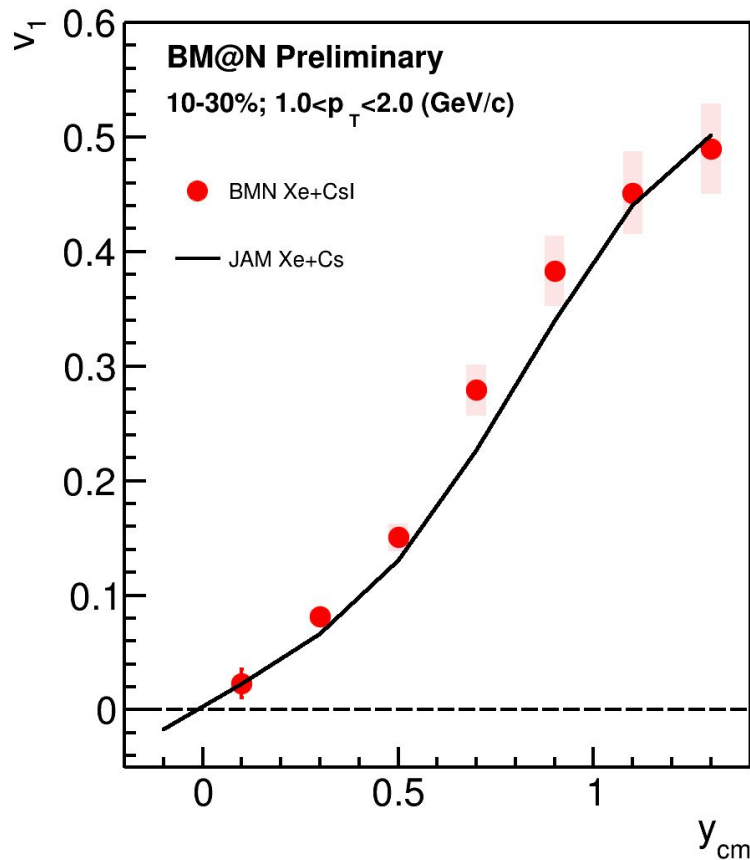
Data is corrected for  $p_T$ - $y$  acceptance

# DATA: $R_1$ in Xe+Cs(I) collisions



All the estimations for symmetry plane resolutions are in a good agreement

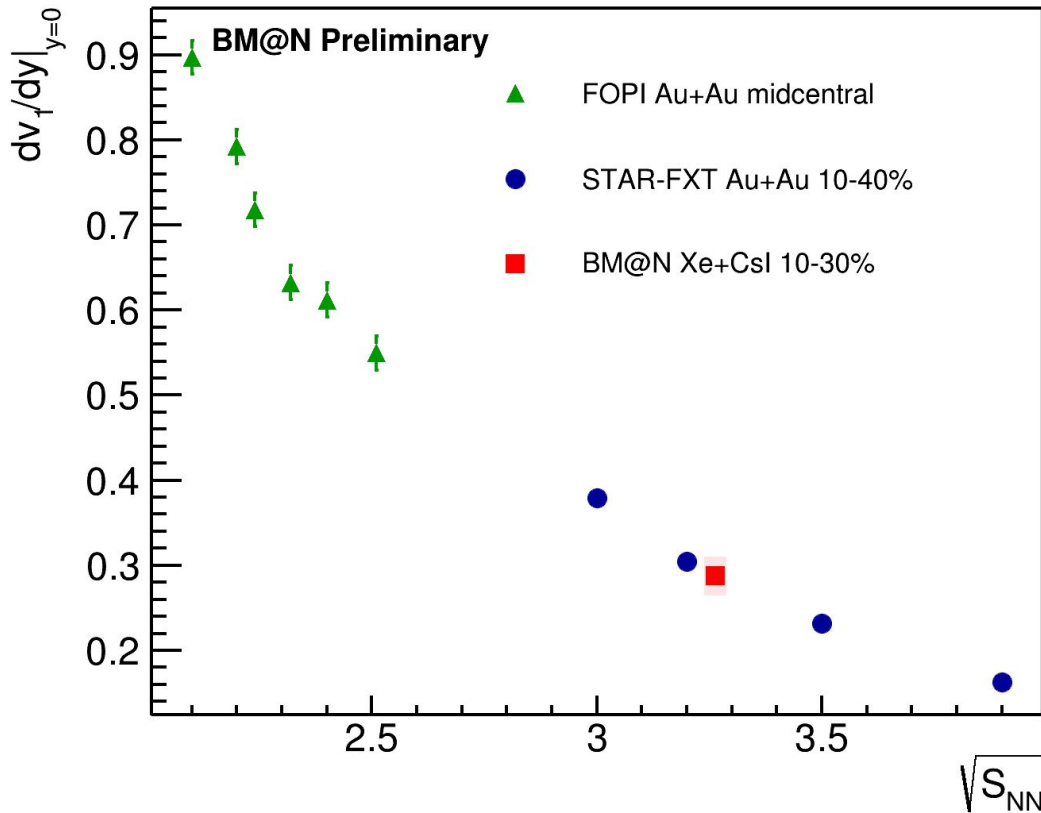
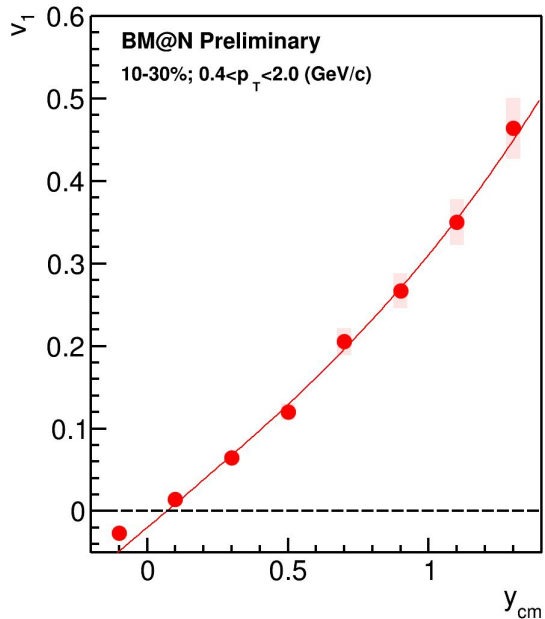
# $v_1$ as a function of $p_T$ and $y$



JAM model describes  $v_1(y)$  well



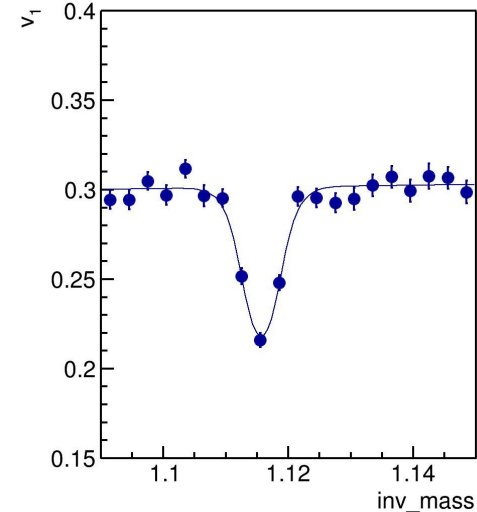
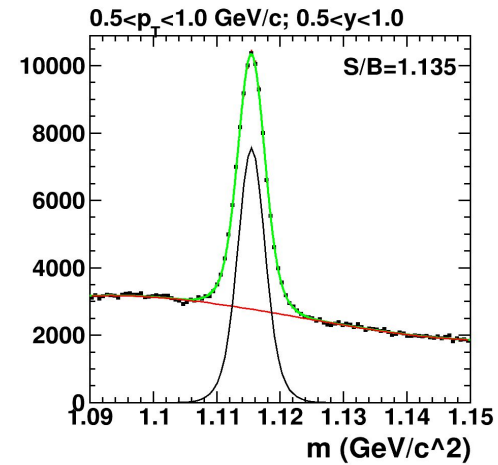
# $dv_1/dy|_{y=0}$ vs collision energy



$dv_1/dy$  is in a good agreement with the world data

# Outlook

- 2025-2026 we expect the Beam-Energy scan program (2A, 3A, 4A GeV)
- The results for higher-harmonics flow is in the process of analysis
- The analysis for  $\Lambda v_1$  is undergoing  
See V.Troshin talk
- Started the analysis for d flow

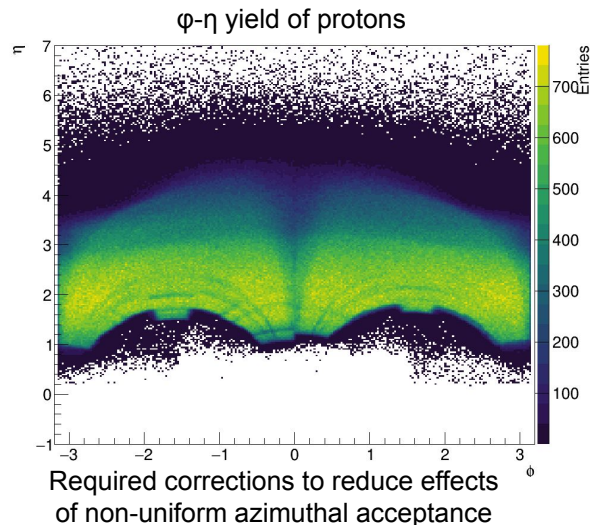


# Summary

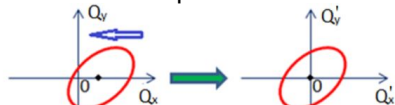
- Directed flow of protons is measured multidifferentially as a function of  $p_T$ ,  $y$  and centrality
- The JAM model describes the  $v_1(y)$  reasonably well in high transverse momentum region
- The directed flow slope at midrapidity  $dv_1/dy|_{y=0}$  was extracted
- The results for directed flow slope  $dv_1/dy$  of protons are in a good agreement with the world data

# Performance Analysis

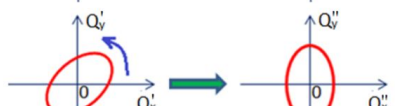
# Azimuthal asymmetry of the BM@N acceptance



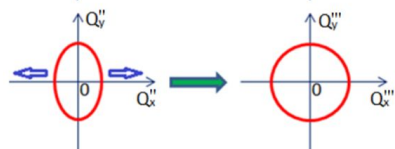
1. Recentering



2. Twist

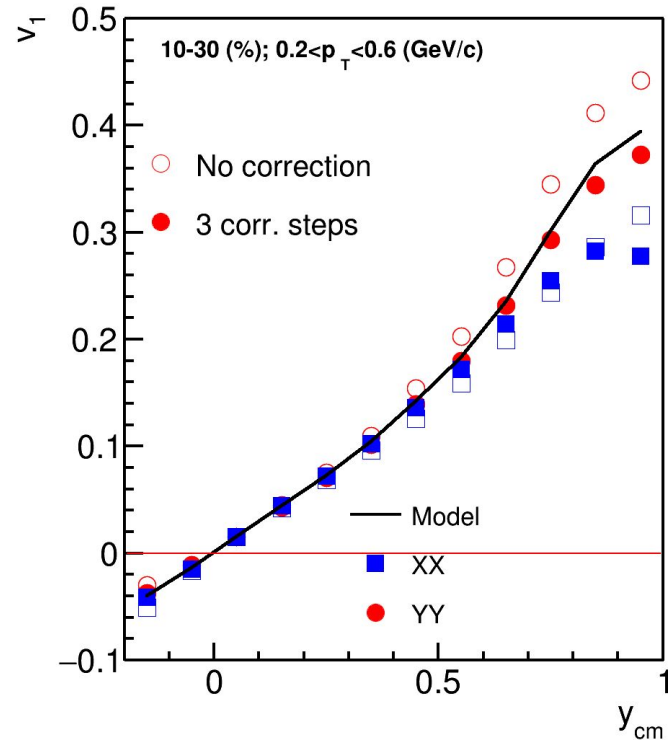


3. Rescaling



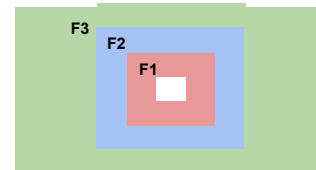
Corrections are based on method in:

I. Selyuzhenkov and S. Voloshin PRC77, 034904 (2008)

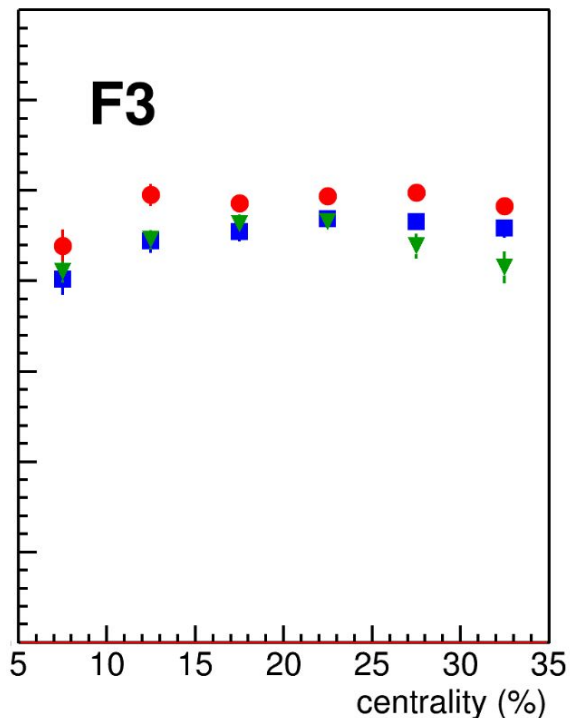
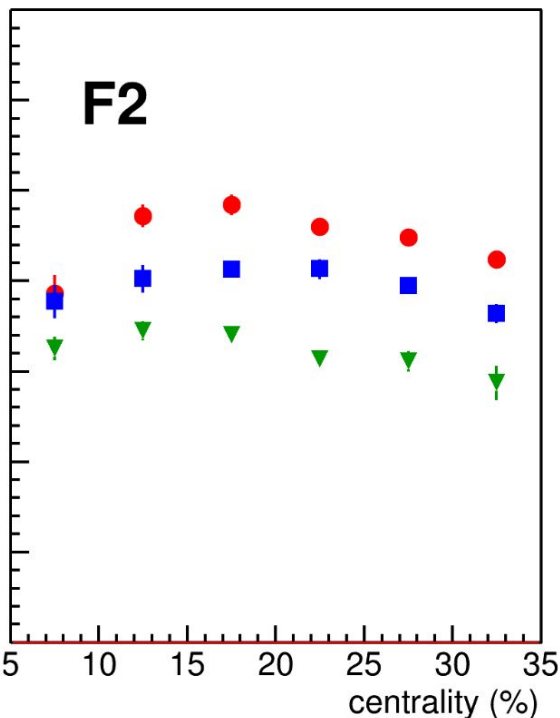
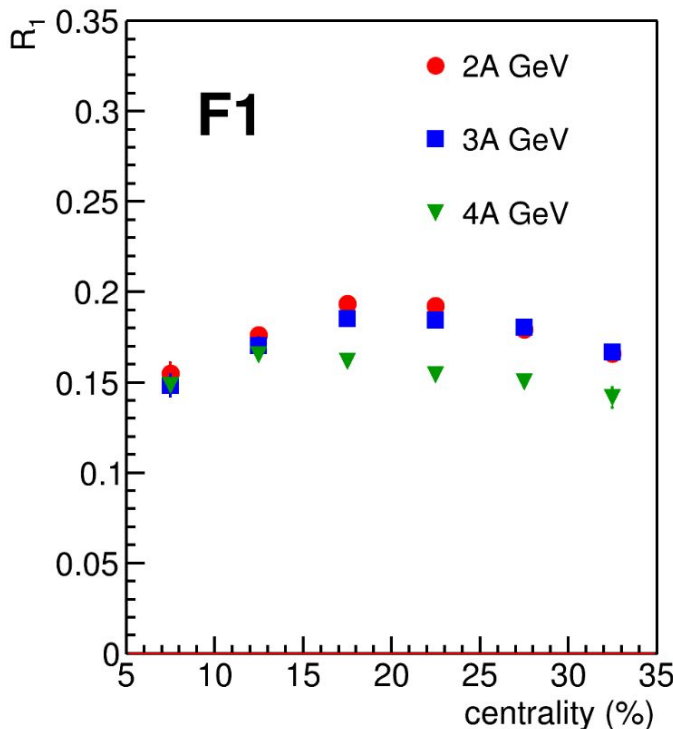


- Better agreement after rescaling for YY
- XX component has too large bias (due to magnetic field)

# Performance study: R1

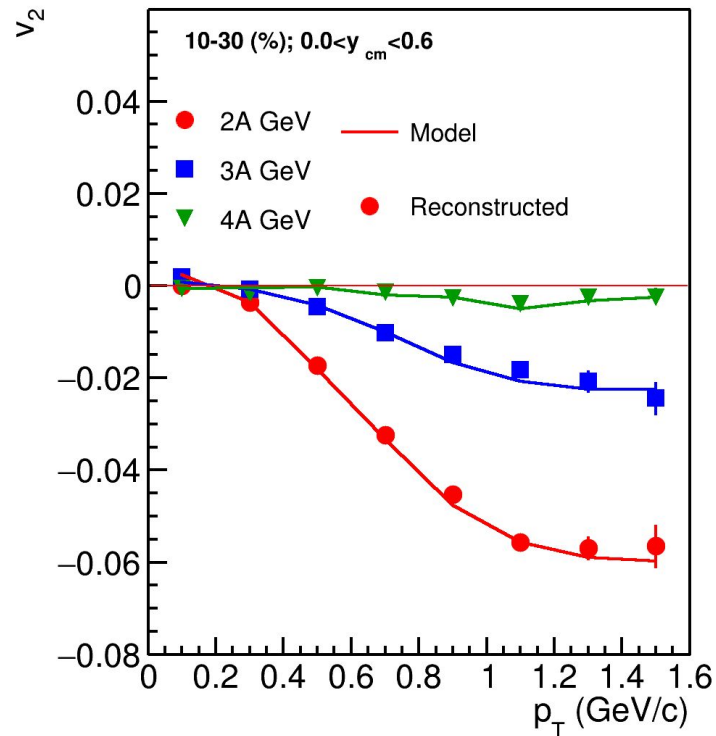
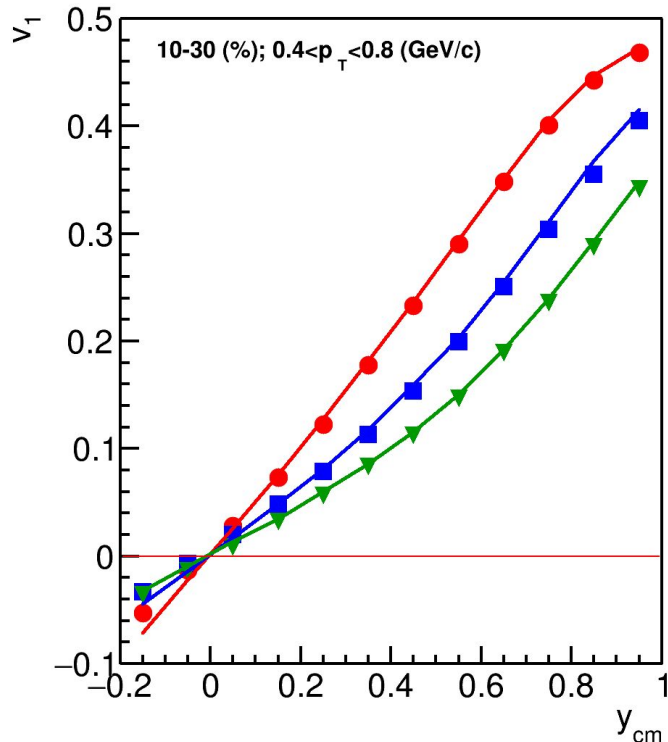


DCMQGSM-SMM



Resolution is lower for higher energies due to lower  $v_1$

# Performance study: $v_1$ and $v_2$ in Xe+Cs (JAM)

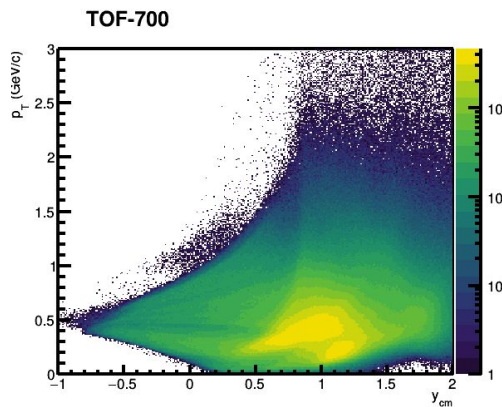
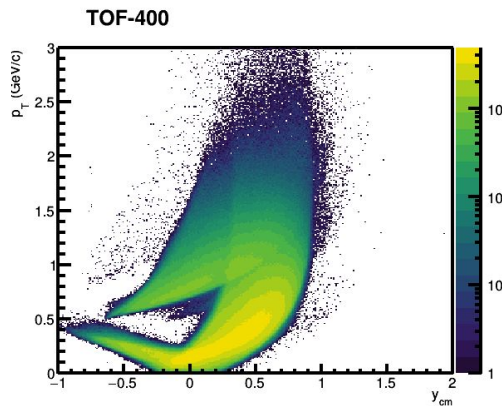
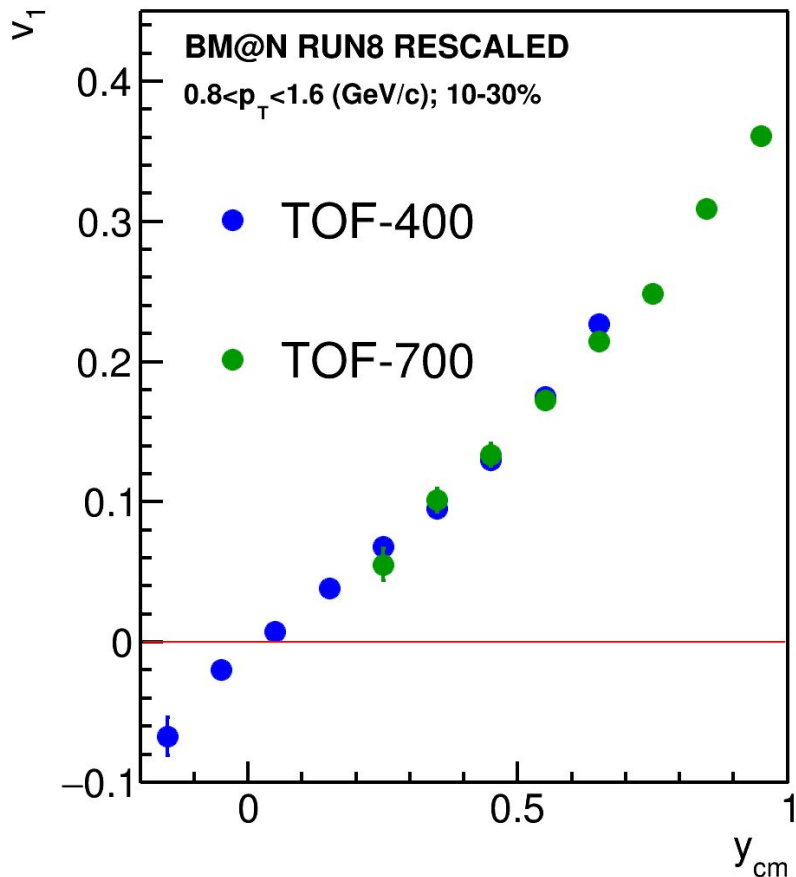


- Good agreement between reconstructed and pure model data for all three energies

# Data Analysis

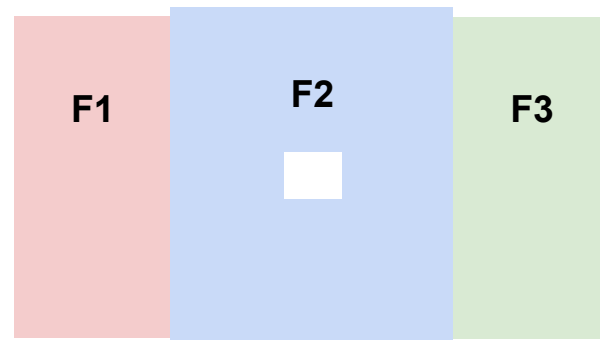
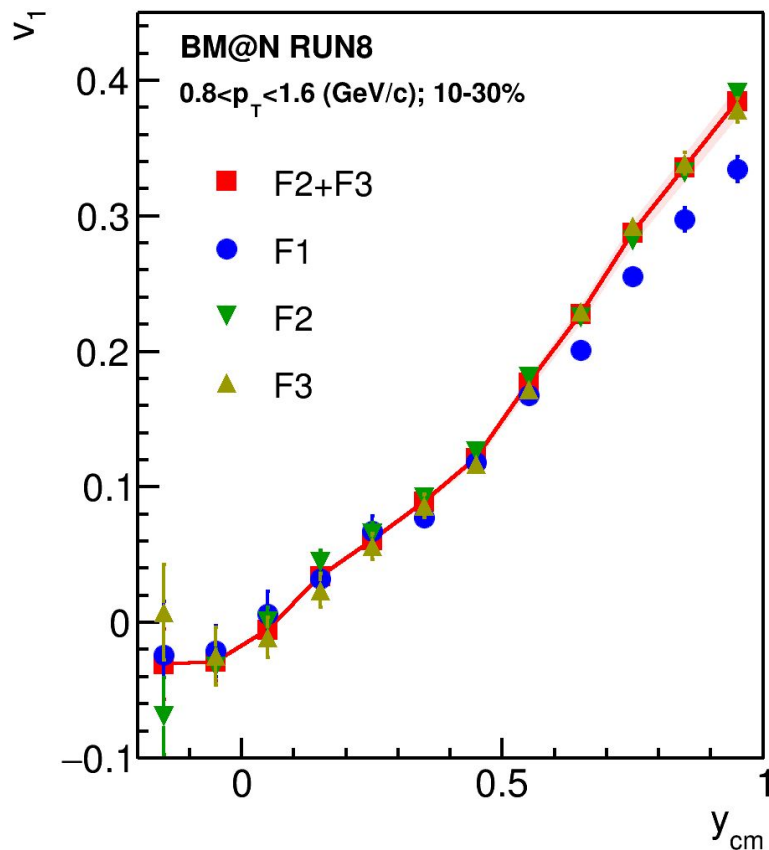


# Comparison of the TOF performances



The results from TOF-400 and TOF-700 are in a good agreement

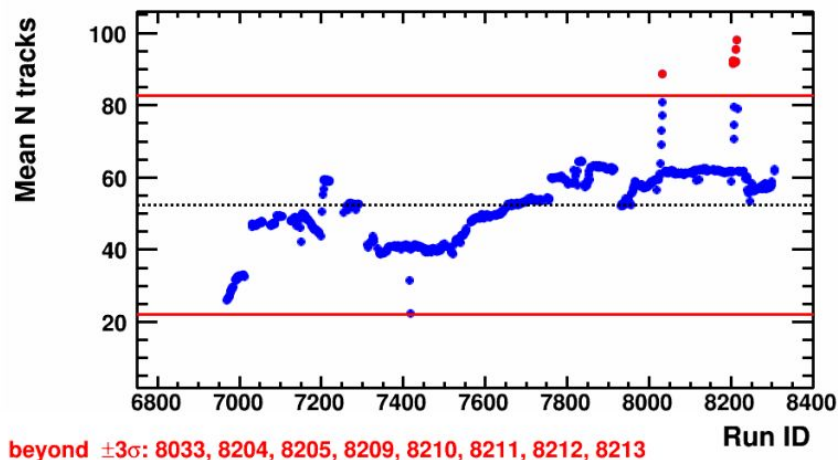
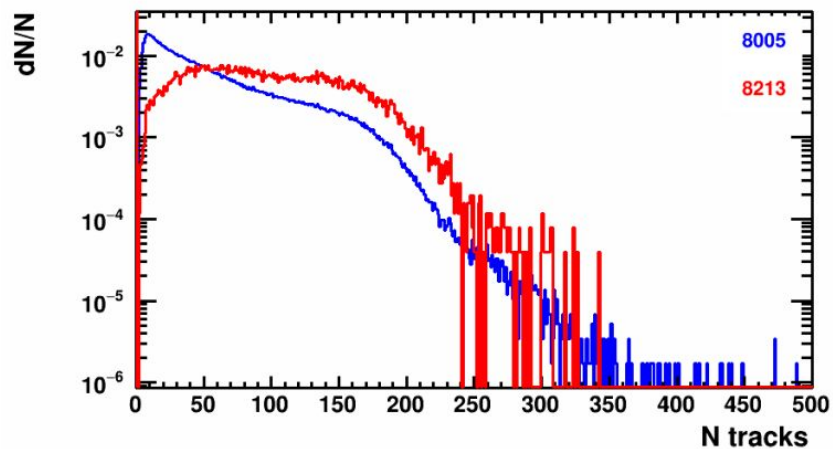
# Systematics due to symmetry plane estimation (non-flow)



The systematics is below 3%

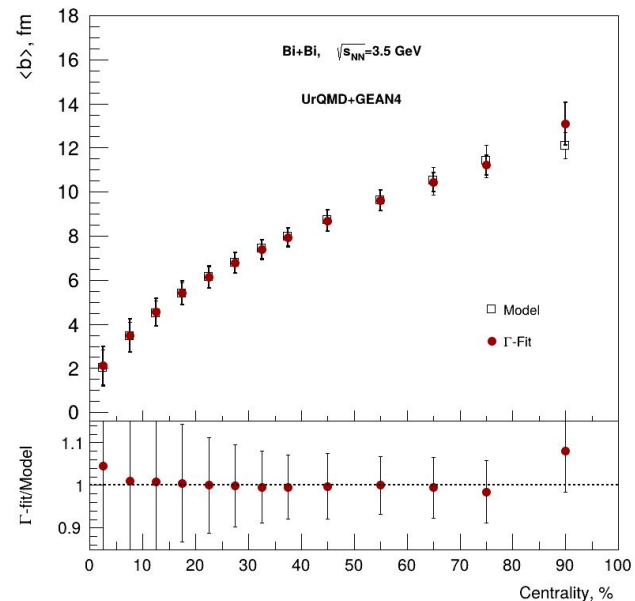
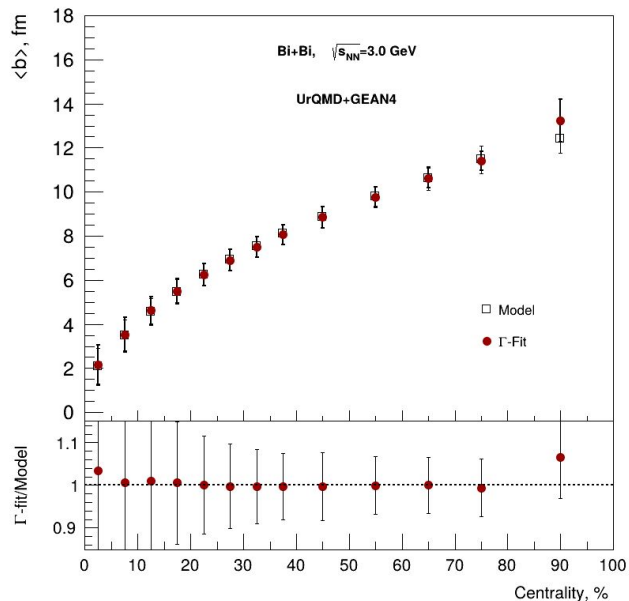
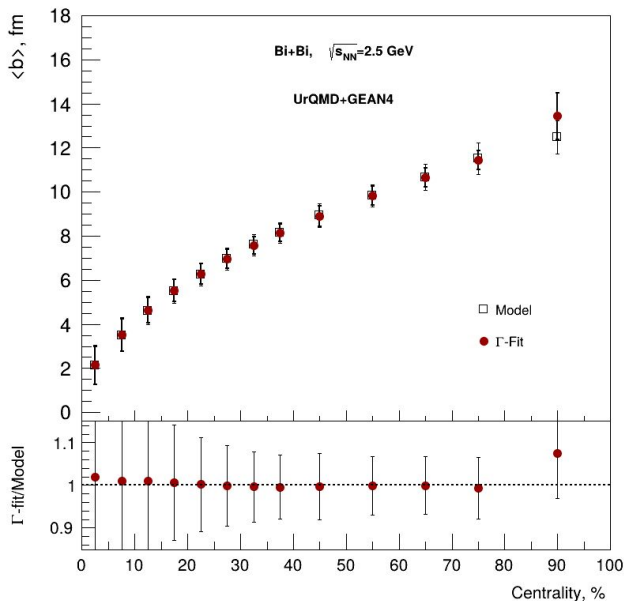
# Backup

# Quality assurance for the recent data



The preliminary list of bad runs based on QA study [18M events] RunId: 6968, 6970, 6972, 6973, 6975, 6976, 6977, 6978, 6979, 6980, 6981, 6982, 6983, 6984, 7313, 7326, 7415, 7417, 7435, 7517, 7520, 7537, 7538, 7542, 7543, 7545, 7546, 7547, 7573, 7575, 7657, 7659, 7679, 7681, 7843, 7847, 7848, 7850, 7851, 7852, 7853, 7855, 7856, 7857, 7858, 7859, 7865, 7868, 7869, 7907, 7932, 7933, 7935, 7937, 7954, 7955, 8018, 8031, 8032, 8033, 8115, 8121, 8167, 8201, 8204, 8205, 8208, 8209, 8210, 8211, 8212, 8213, 8215, 8289.

# Centrality determination: $\langle b \rangle$ vs Centrality



Cuts on tracks:

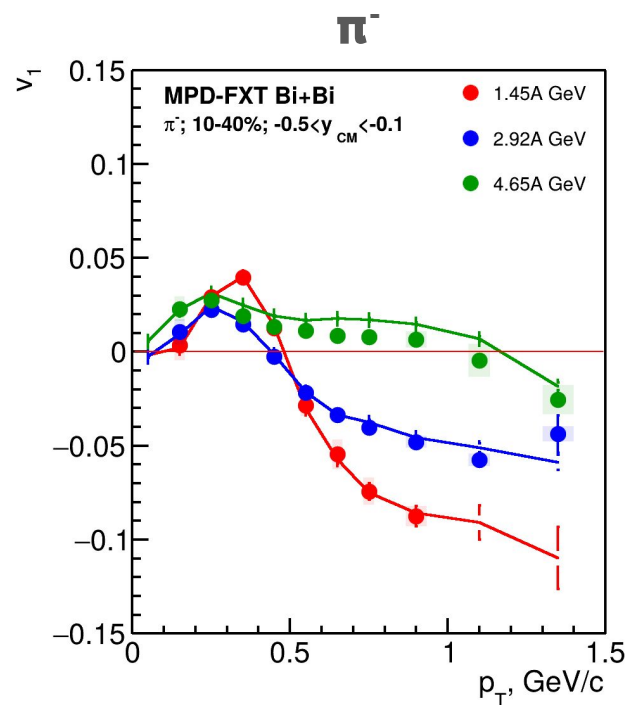
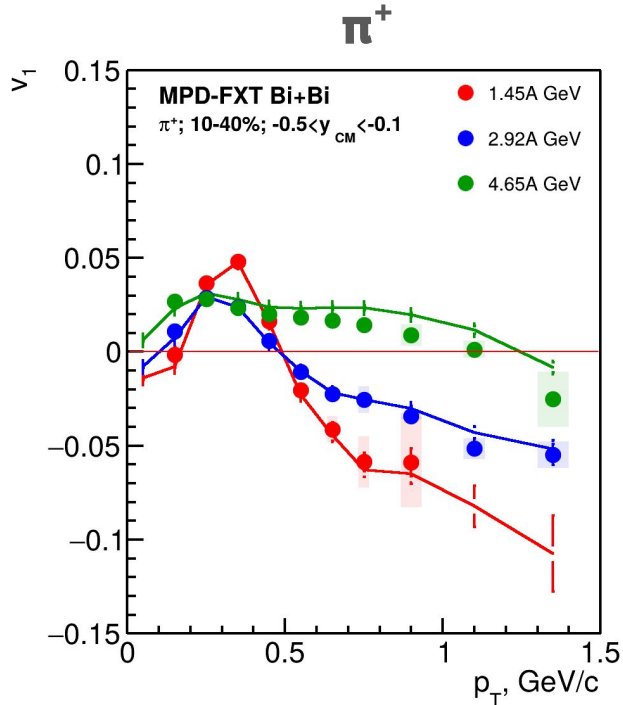
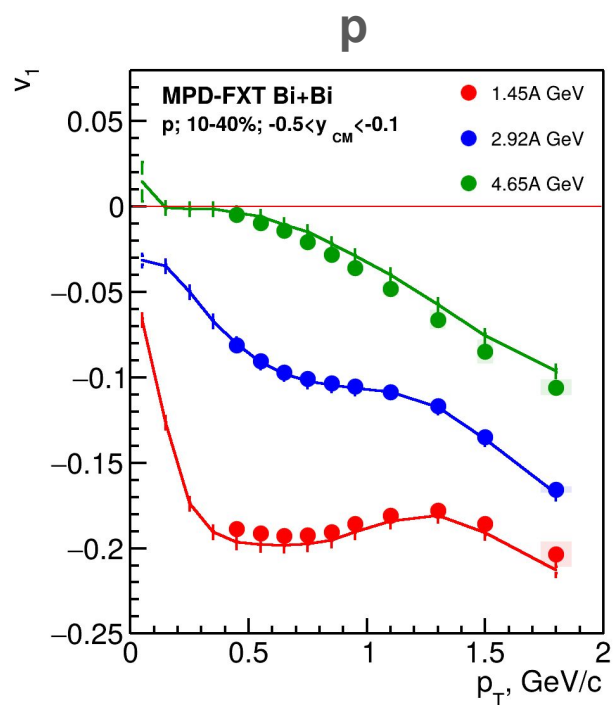
- $N_{\text{hits}} > 16$
- $0 < \eta < 2$

Good agreement between fit and data

Multiplicity-based centrality determination using inverse Bayes was used

# Results: $v_1(p_T)$

Systematics: xx, yy, F1, F2, F3

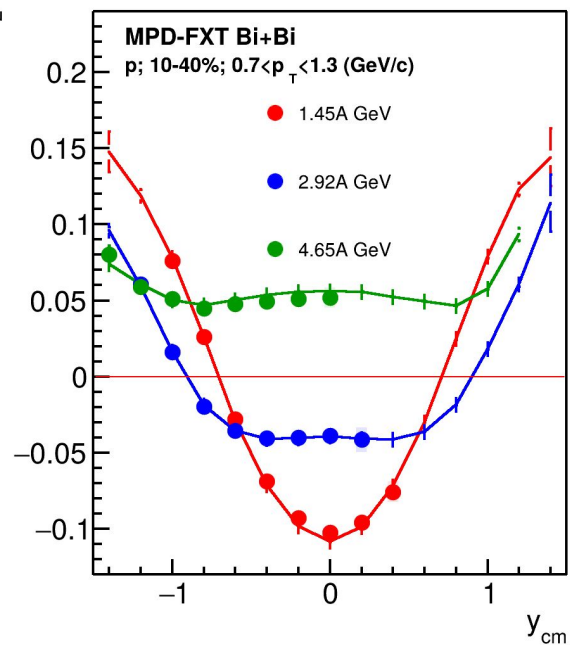


Good agreement with MC data

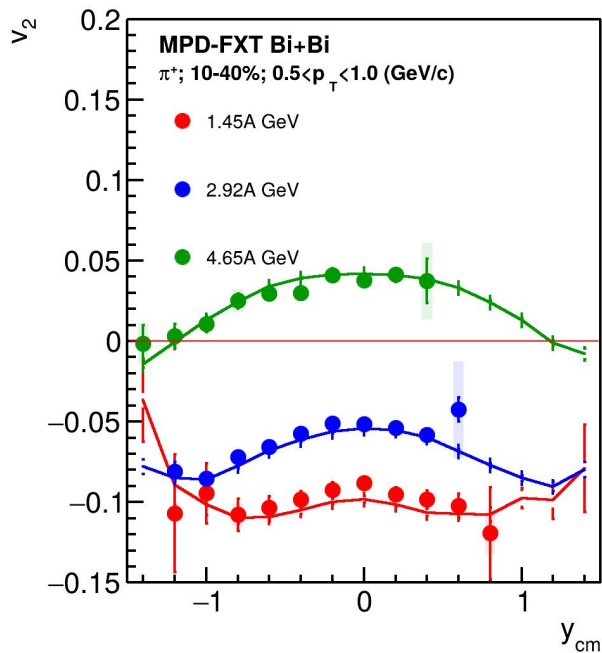
# Results: $v_2(y)$

Systematics: xxx, xyy

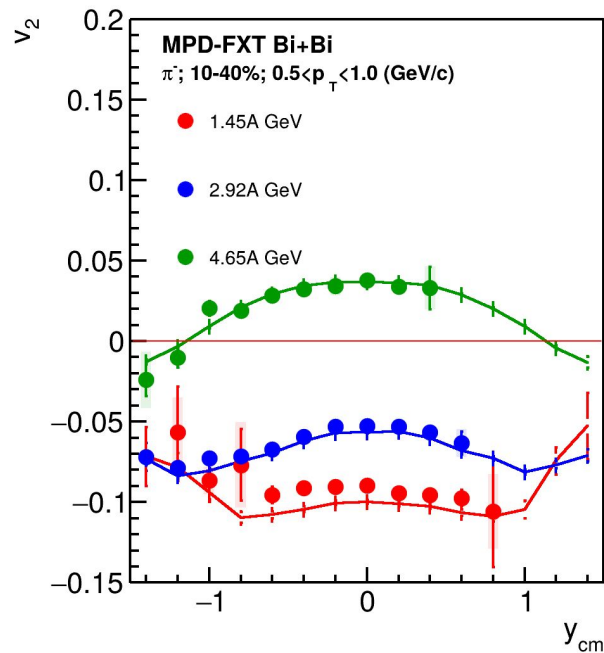
**p**



**$\pi^+$**



**$\pi^-$**



Good agreement with MC data

# The Bayesian inversion method ( $\Gamma$ -fit)

Relation between multiplicity  $N_{ch}$  and impact parameter  $b$  is defined by the fluctuation kernel:

$$P(N_{ch}|c_b) = \frac{1}{\Gamma(k(c_b))\theta^k} N_{ch}^{k(c_b)-1} e^{-N_{ch}/\theta} \quad \frac{\sigma^2}{\langle N_{ch} \rangle} = \theta \approx const, k = \frac{\langle N_{ch} \rangle}{\theta}$$

$$c_b = \int_0^b P(b') db' - \text{centrality based on impact parameter}$$

Mean multiplicity as a function of  $c_b$  can be defined as follows:

$$\langle N_{ch} \rangle = N_{knee} \exp\left(\sum_{j=1}^3 a_j c_b^j\right) \quad N_{knee}, \theta, a_j - 5 \text{ parameters}$$

Fit function for  $N_{ch}$  distribution:

$b$ -distribution for a given  $N_{ch}$  range:

$$P(N_{ch}) = \int_0^1 P(N_{ch}|c_b) dc_b \quad P(b|n_1 < N_{ch} < n_2) = P(b) \frac{\int_{n_1}^{n_2} P(N_{ch}|b) dN_{ch}}{\int_{n_1}^{n_2} P(N_{ch}) dN_{ch}}$$

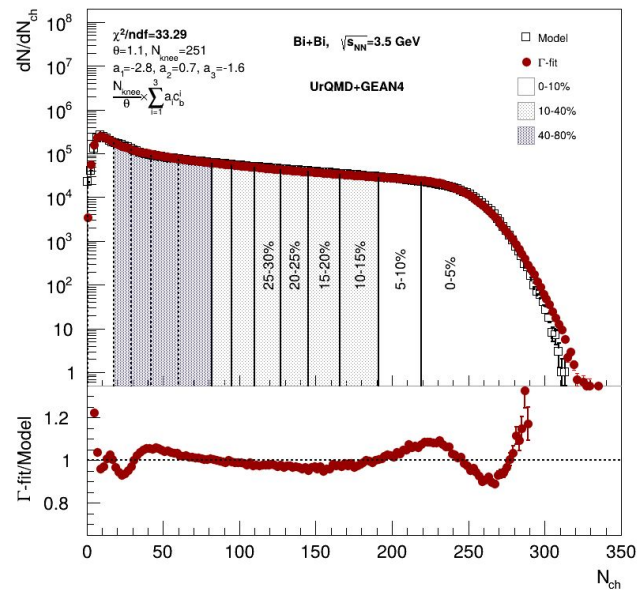
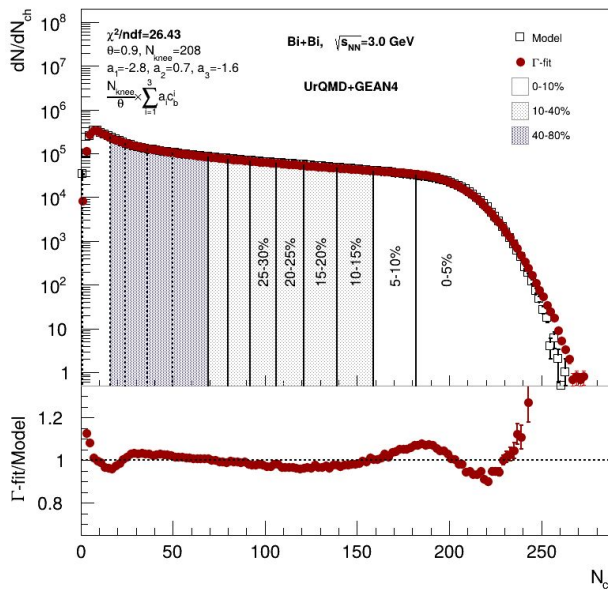
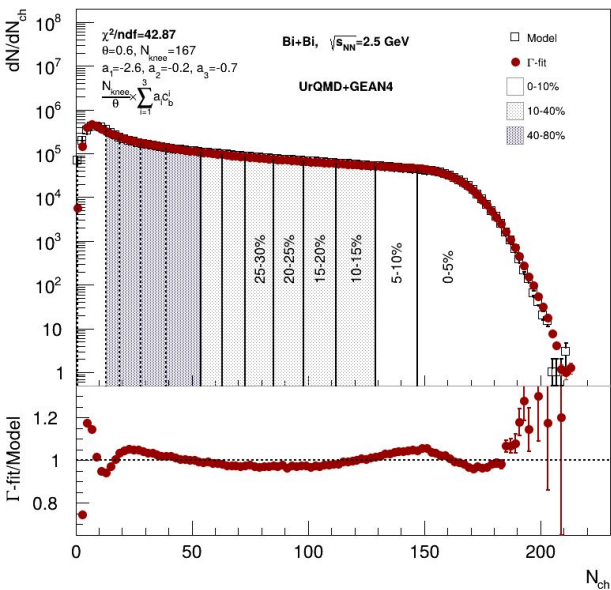
**2 main steps of the method:**

Fit experimental (model) distribution with  $P(N)$

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



# Centrality determination: multiplicity fit



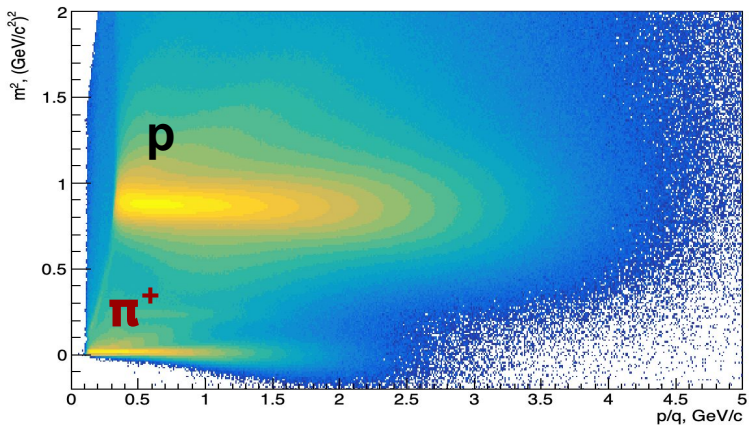
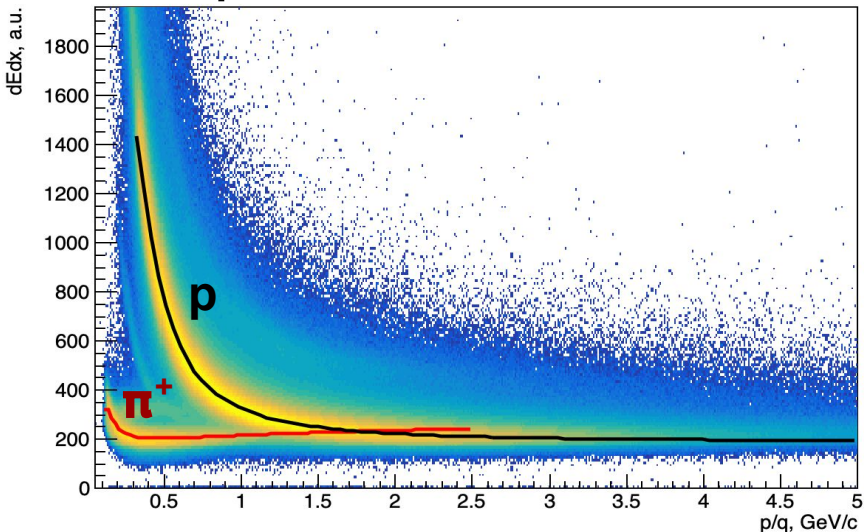
Cuts on tracks:

- $N_{hits} > 16$
- $0 < \eta < 2$

Good agreement between fit and data

Multiplicity-based centrality determination ( $\Gamma$ -fit) was used

# PID procedure



Fit  $dE/dx$  distributions with Bethe-Bloch parametrization:

$$f(\beta\gamma) = \frac{p_1}{\beta^{p_4}} \left( p_2 - \beta^{p_4} - \ln \left( p_3 + \frac{1}{(\beta\gamma)^{p_5}} \right) \right)$$

$$\beta^2 = \frac{p^2}{m^2 + p^2}, \beta\gamma = \frac{p}{m} \quad p_i - \text{fit parameters}$$

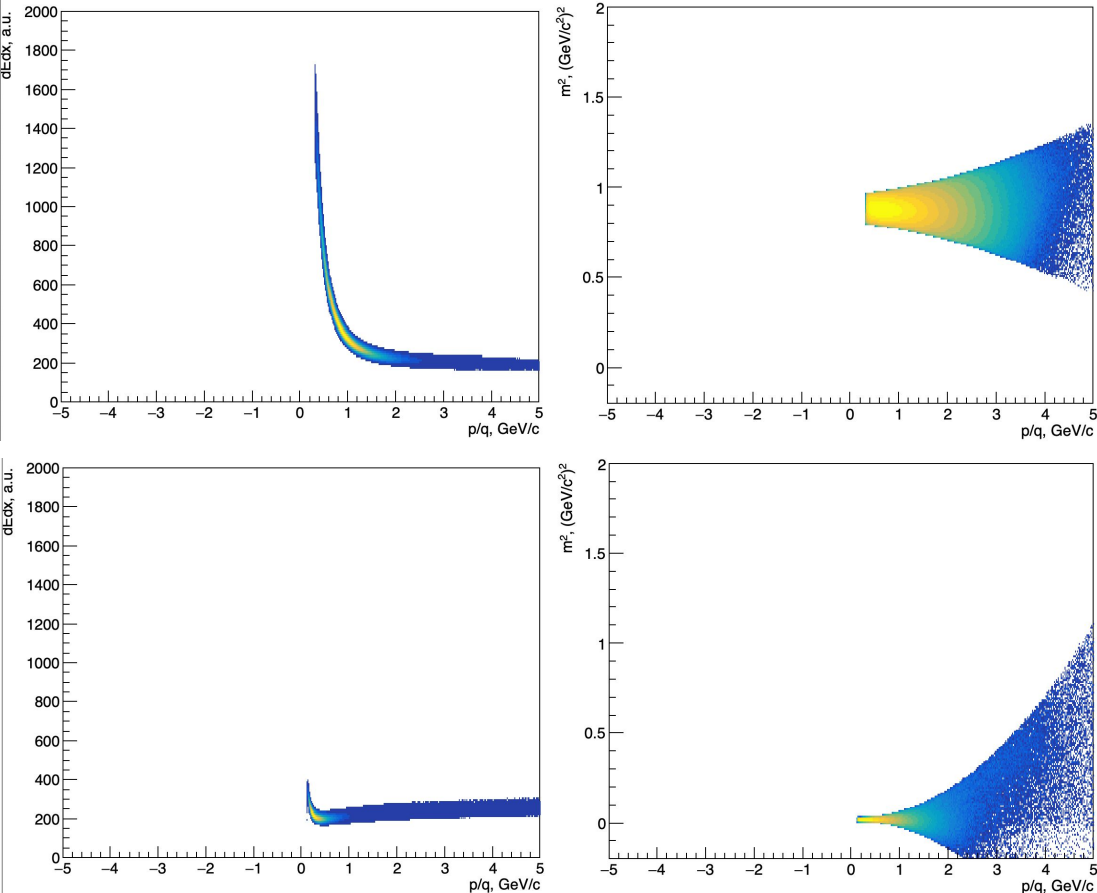
Fit  $(dE/dx - f(\beta\gamma))/f(\beta\gamma)$  with gaus in the slices of  $p/q$  and get  $\sigma_p(dE/dx)$

Fit  $m^2$  with gaus in the slices of  $p/q$  and get  $\sigma_p(m^2)$

**$(dE/dx, m) \rightarrow (x, y)$  coordinates for PID:**

$$x_p = \frac{(dE/dx)^{meas} - (dE/dx)_p^{fit}}{(dE/dx)_p^{fit} \sigma_p^{dE/dx}}, \quad y_p = \frac{m^2 - m_p^2}{\sigma_p^{m^2}}$$

# PID procedure: Results



$$x_p = \frac{(dE/dx)^{meas} - (dE/dx)_p^{fit}}{(dE/dx)_p^{fit} \sigma_p^{dE/dx}}$$

$$y_p = \frac{m^2 - m_p^2}{\sigma_p^{m^2}}$$

Protons:

$$\sqrt{x_p^2 + y_p^2} < 2, \sqrt{x_\pi^2 + y_\pi^2} > 3$$

Pions ( $\pi^+$ ):

$$\sqrt{x_\pi^2 + y_\pi^2} < 2, \sqrt{x_p^2 + y_p^2} > 3$$

Pions ( $\pi^-$ ):

charge < 0

# (y-pt) distribution, efficiency and $\delta p_T$ (protons)

$$\text{eff} = \frac{\frac{dN}{dydp_T}(\text{reco})}{\frac{dN}{dydp_T}(\text{sim})}$$

$$\Delta p_T = \frac{|p_T^{\text{reco}} - p_T^{\text{mc}}|}{p_T^{\text{mc}}}$$

**Bi+Bi  $\sqrt{s_{NN}}=2.5$  GeV**

Cuts for reco tracks:

- Nhits>27
- DCA< 1 cm
- PID (TPC+TOF)
- Primary (DCA<1 cm)

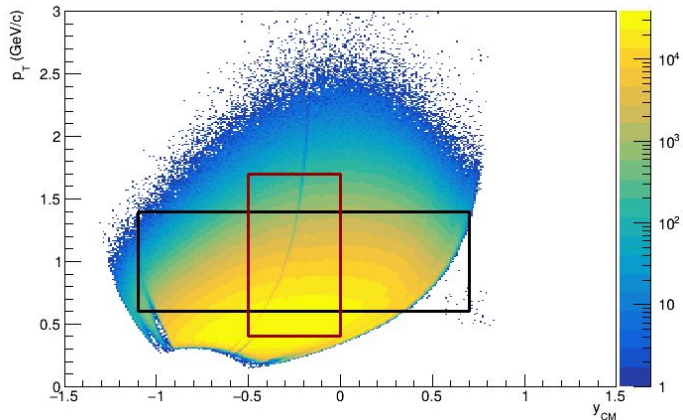
Cuts for sim particles:

- PID (pdg code)
- Primary (motherId)

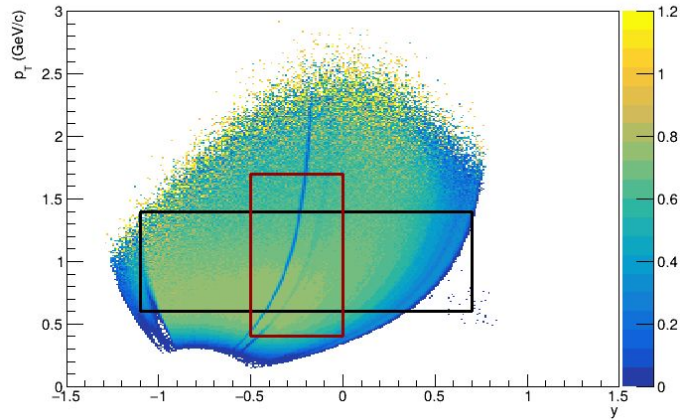
**Black box:** acceptance window for  $v_n(y)$

**Red box:** acceptance window for  $v_n(p_T)$

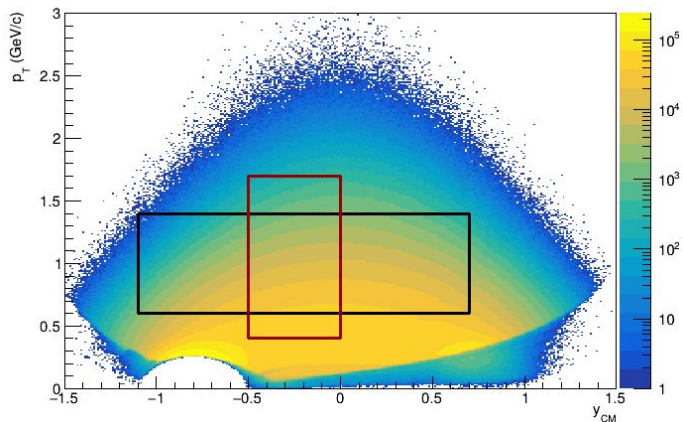
Reconstructed protons Ycm-pT



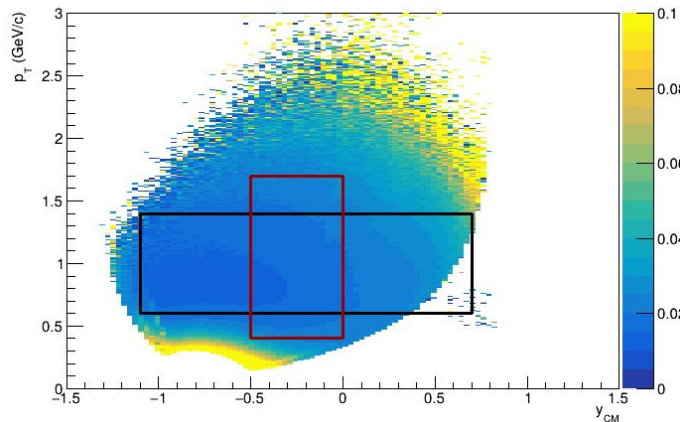
Efficiency (Y-pT) of primary protons



Simulated protons Ycm-pT



Pt-resolution for reconstructed protons in Ycm-pT plane



# Flow vectors

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

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

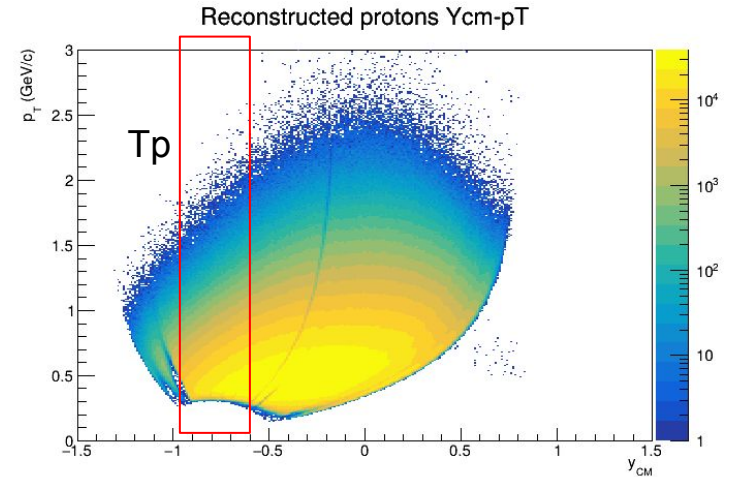
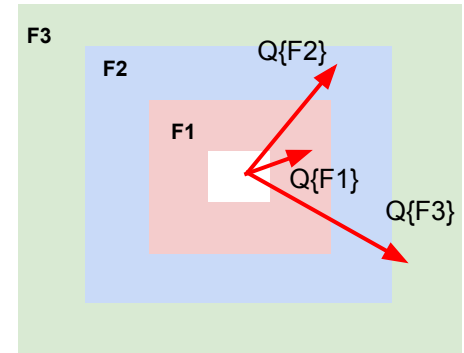
where  $\phi$  is the azimuthal angle

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

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

$\Psi_n^{EP}$  is the event plane angle

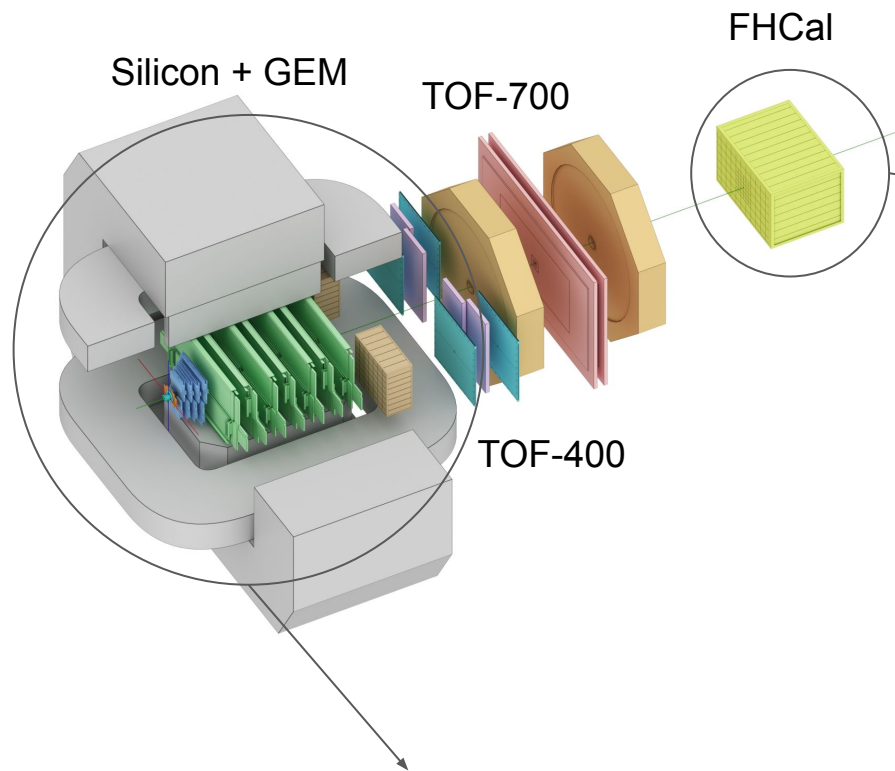
Modules of FHCAL divided into 3 groups



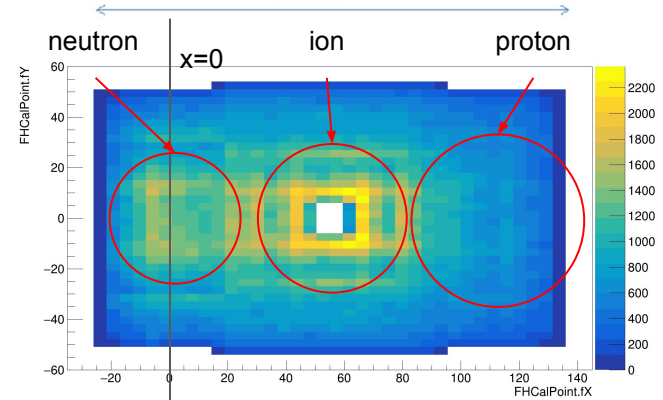
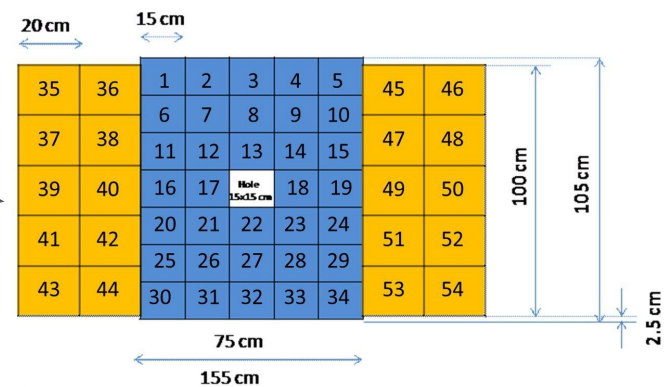
**Additional subevents from tracks not pointing at FHCAL:**  
**Tp: p;  $-1.0 < y < -0.6$ ;**



# The BM@N experiment (GEANT4 simulation for RUN8)

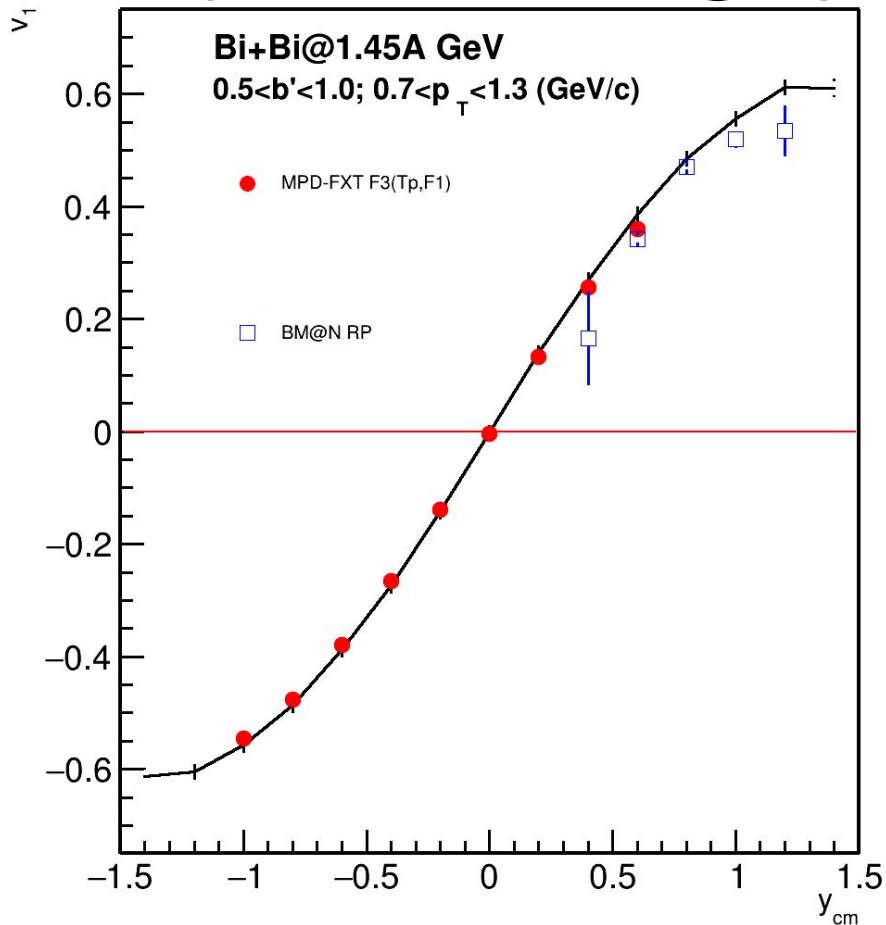


Square-like tracking system within the magnetic field deflecting particles along X-axis



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

# Comparison with BM@N performance



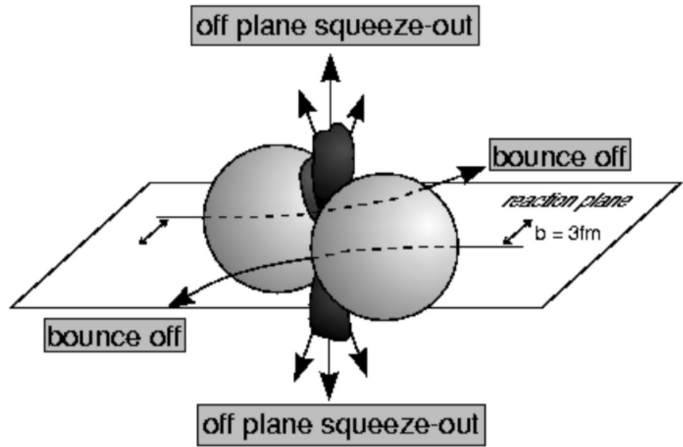
BM@N TOF system (TOF-400 and TOF-700) has poor midrapidity coverage at  $\sqrt{s_{NN}} = 2.5$  GeV

- One needs to check higher energies ( $\sqrt{s_{NN}} = 3, 3.5$  GeV)
- More statistics are required due to the effects of magnetic field in BM@N:
  - Only “yy” component of  $\langle uQ \rangle$  and  $\langle QQ \rangle$  correlation can be used

Despite the challenges, both MPD-FXT and BM@N can be used in  $v_n$  measurements:

- To widen rapidity coverage
- To perform a cross-check in the future

# Anisotropic flow & spectators



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

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

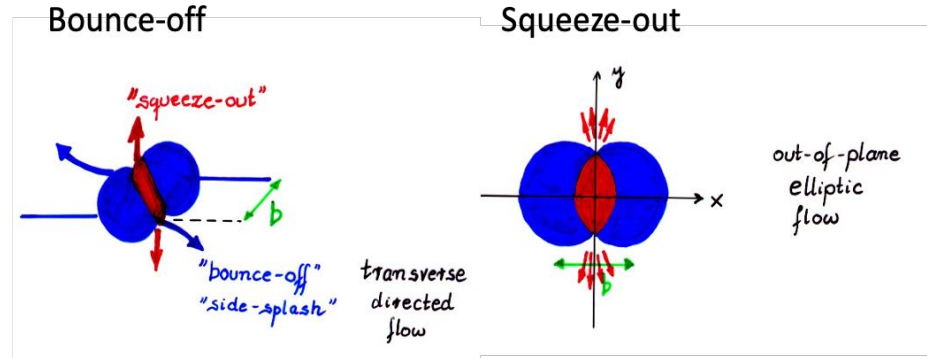
Anisotropic flow:

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

$v_1$  - directed flow,  $v_2$  - elliptic flow

## Anisotropic flow is sensitive to:

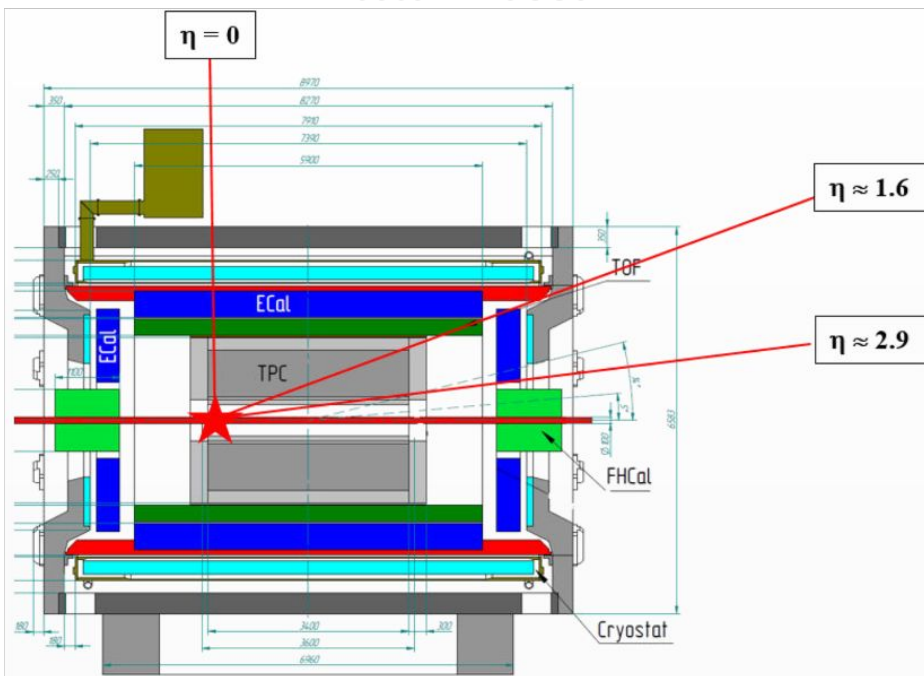
- **Compressibility of the created matter**  
 $(t_{exp} = R/c_s, c_s = c\sqrt{dp/d\varepsilon})$
- **Time of the interaction between overlap region and spectators**  
 $(t_{pass} = 2R/\gamma_{CM}\beta_{CM})$





# MPD in Fixed-Target Mode (FXT)

## MPD-FXT



- Model used: UrQMD mean-field
  - Bi+Bi,  $E_{\text{kin}} = 1.45$  AGeV ( $\sqrt{s_{\text{NN}}} = 2.5$  GeV)
  - Bi+Bi,  $E_{\text{kin}} = 2.92$  AGeV ( $\sqrt{s_{\text{NN}}} = 3.0$  GeV)
  - Bi+Bi,  $E_{\text{kin}} = 4.65$  AGeV ( $\sqrt{s_{\text{NN}}} = 3.5$  GeV)
- Point-like target at  $z = -115$  cm
- GEANT4 transport
- Multiplicity-based centrality determination
- PID using information from TPC and TOF
- Primary track selection:  $\text{DCA} < 1$  cm
- Track selection:
  - $N_{\text{hits}} > 27$  (protons),  $N_{\text{hits}} > 22$  (pions)

# Flow vectors

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

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

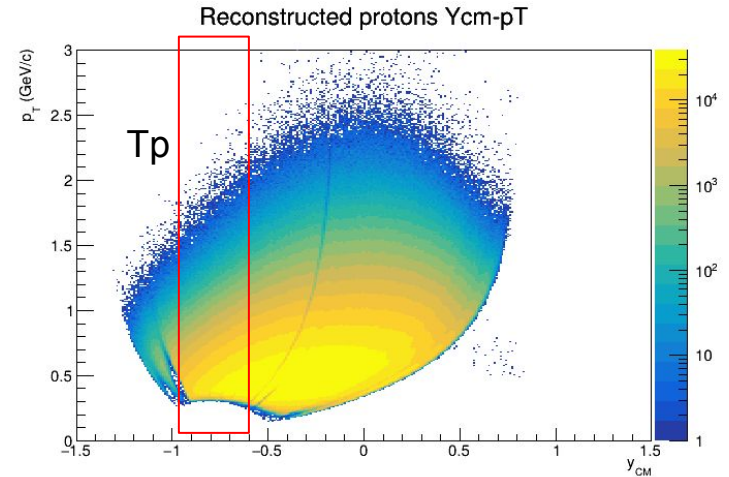
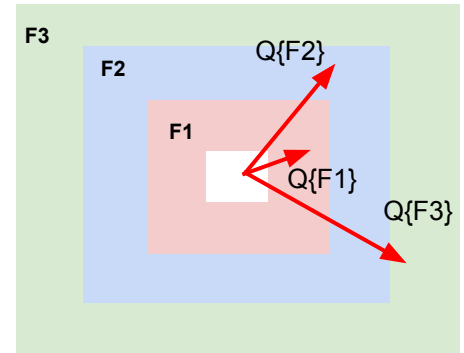
where  $\phi$  is the azimuthal angle

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

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

$\Psi_n^{EP}$  is the event plane angle

Modules of FHCAL divided into 3 groups

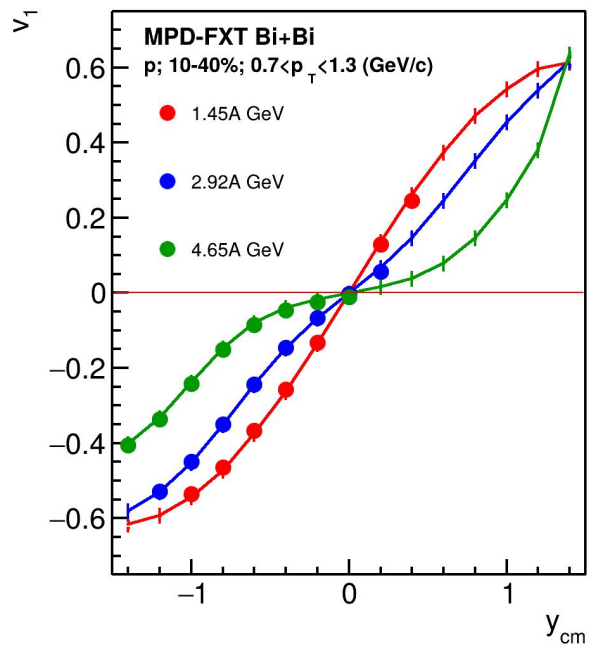


**Additional subevents from tracks not pointing at FHCAL:**  
**Tp: p;  $-1.0 < y < -0.6$ ;**

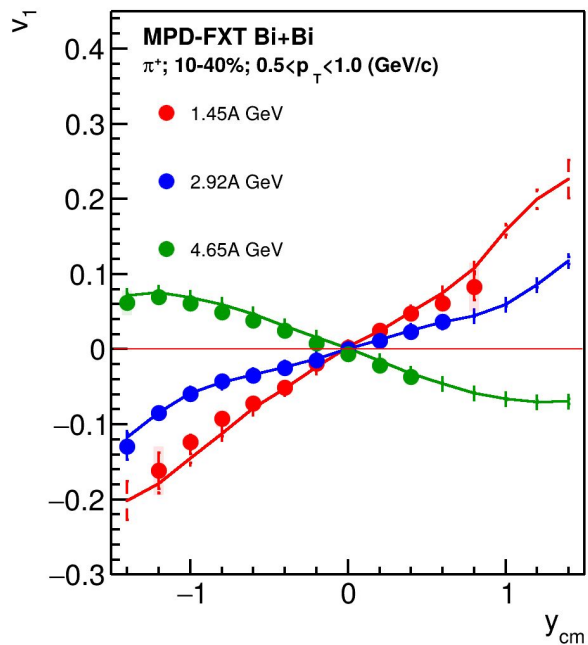
# Results: $v_1(y)$

Systematics: xx, yy, F1, F2, F3

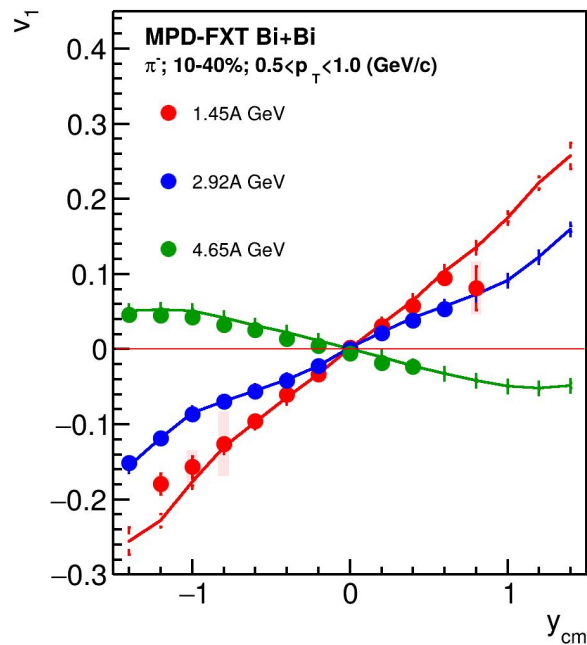
**p**



**$\pi^+$**



**$\pi^-$**

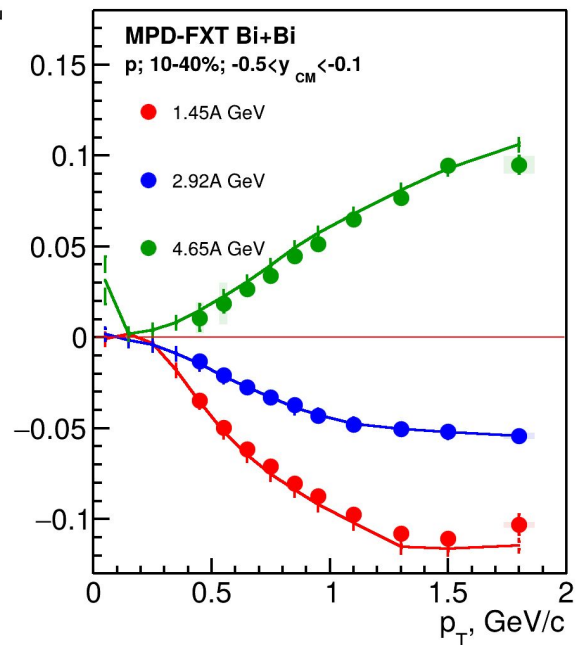


Good agreement with MC data

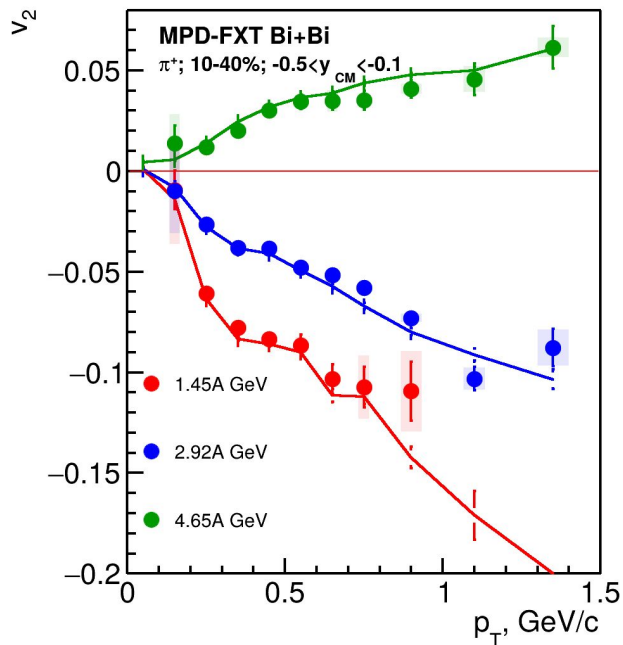
# Results: $v_2(p_T)$

Systematics: xxx, xyy

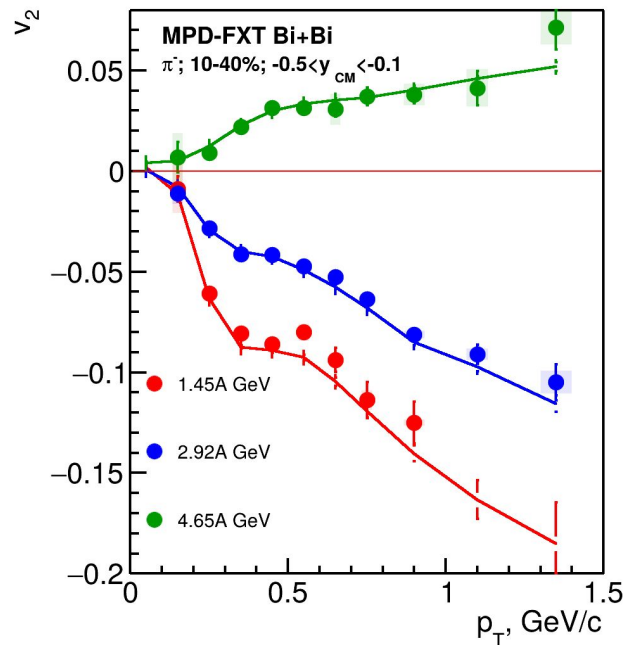
$p$



$\pi^+$

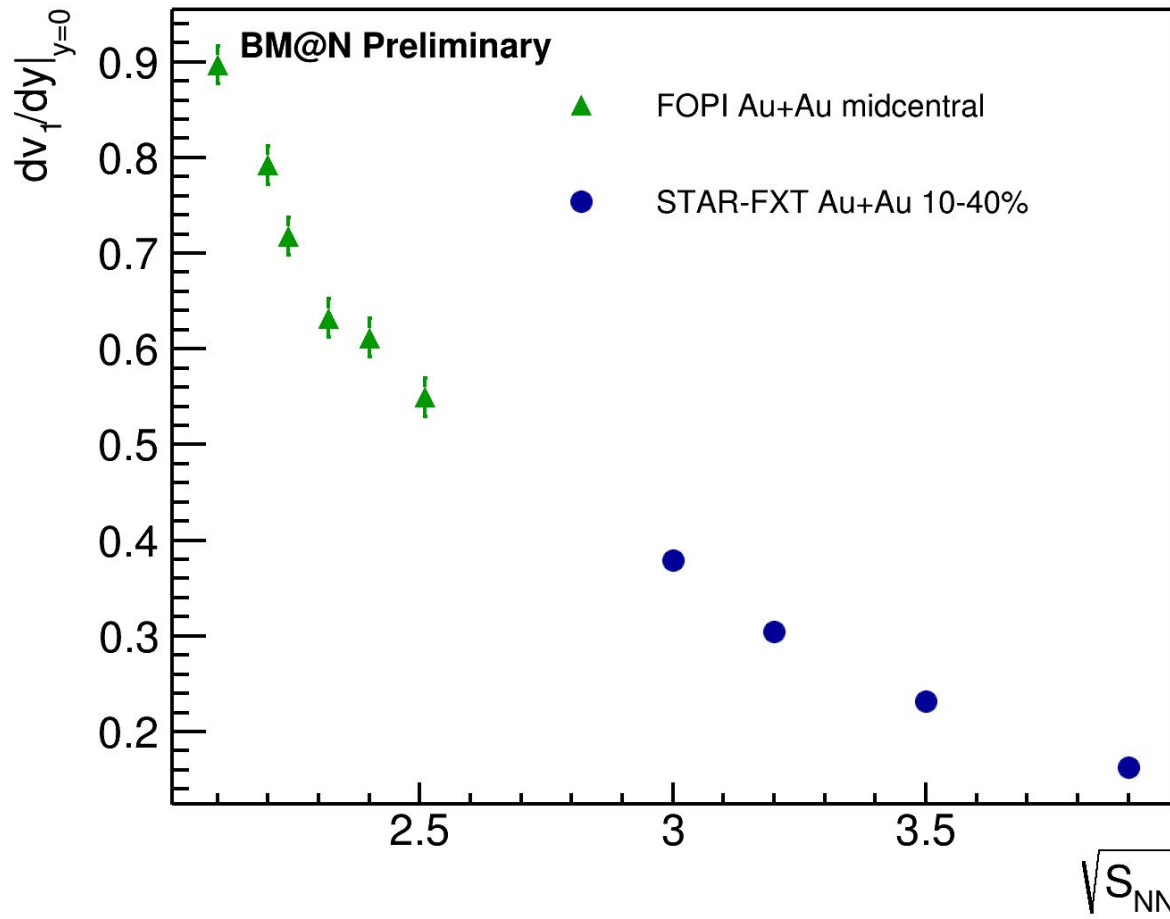


$\pi^-$

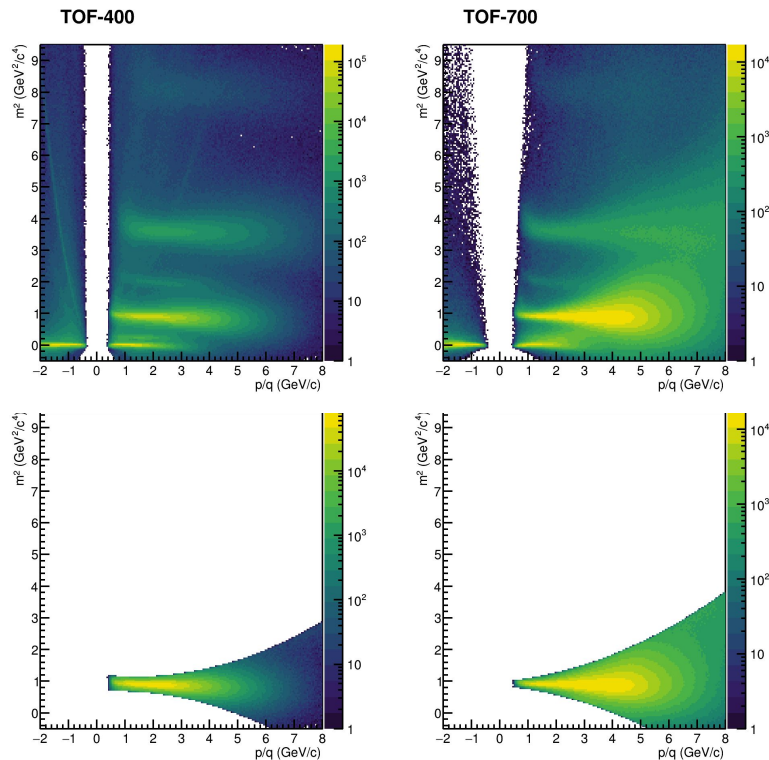
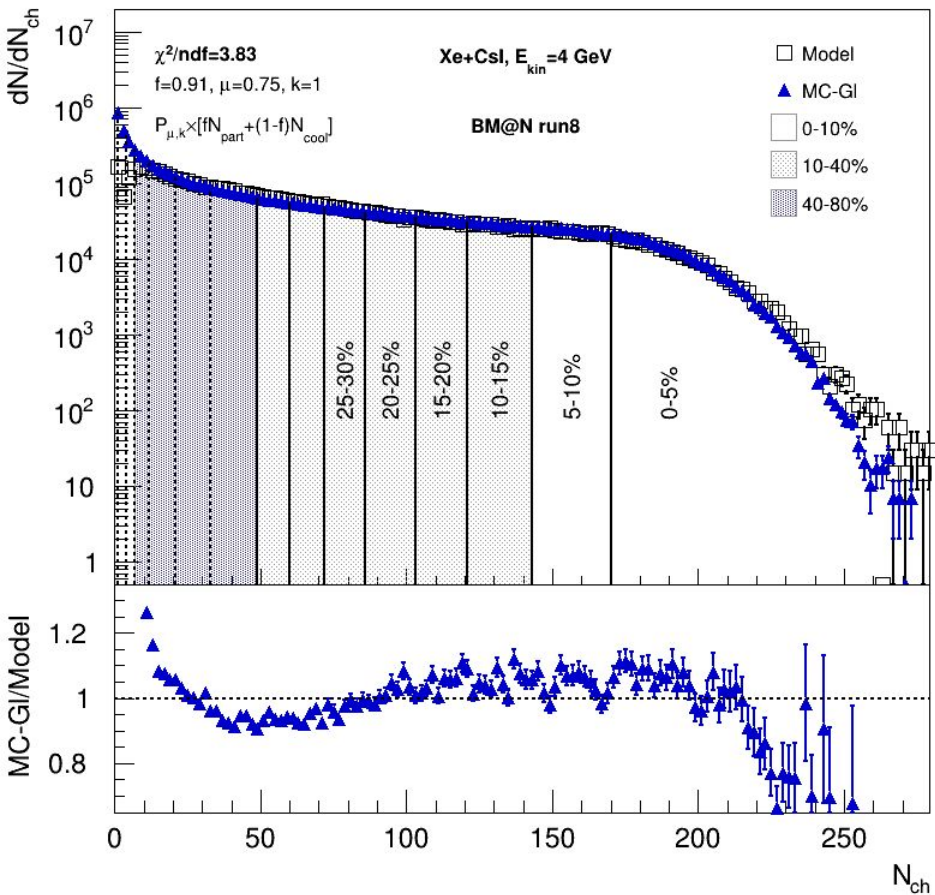


Good agreement with MC data

# $dv_1/dy|_{y=0}$ vs collision energy



# Centrality and particle selection

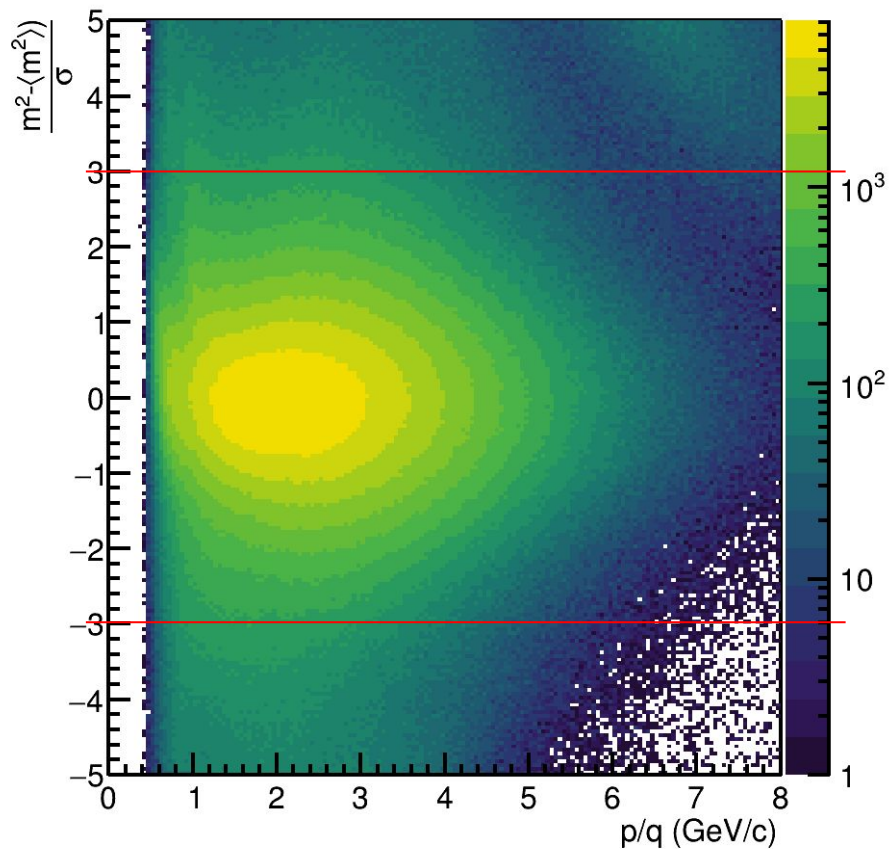


- Half of the recent VF production was analysed
- Event selection criteria (~100M events selected)
  - CCT2 trigger
  - Pile-up cut
  - Number tracks for vertex > 1
- Track selection criteria :  $\chi^2 < 5$ ;  $M_p^2 - 3\sigma < m^2 < M_p^2 + 3\sigma$ ;  $N_{hits} > 52$

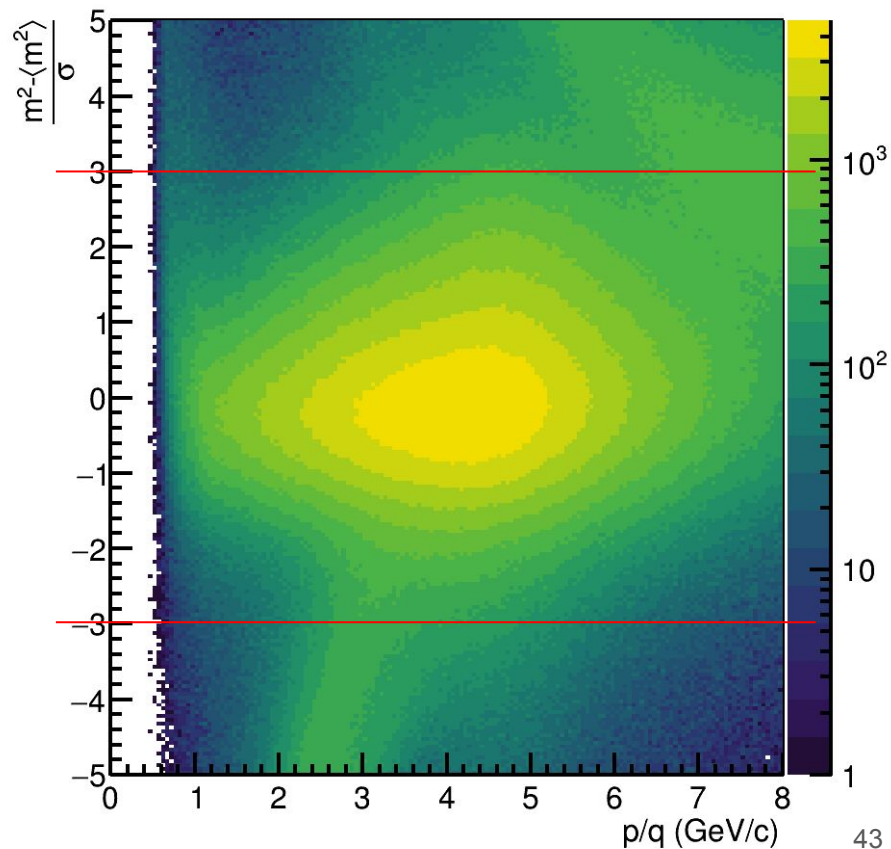


# Proton N-sigma distributions

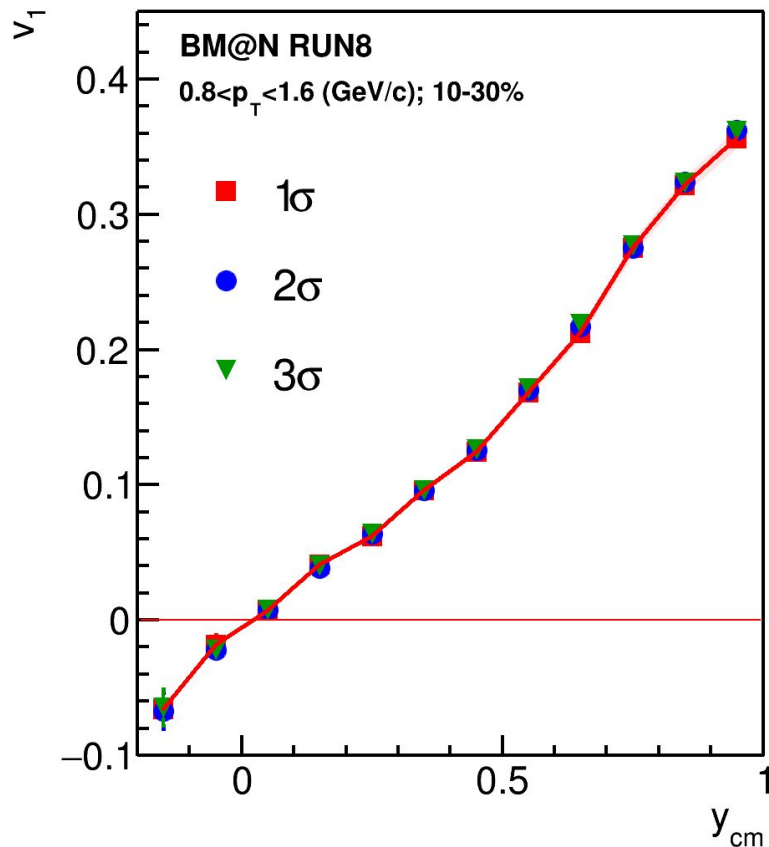
## TOF-400



## TOF-700



# Systematics due to identification and tracking



The systematics is below 2%

