PWG3 Summary

Arkadiy Taranenko for PWG3

XV MPD Collaboration Meeting, Dubna, Russia, 15-17 April 2025

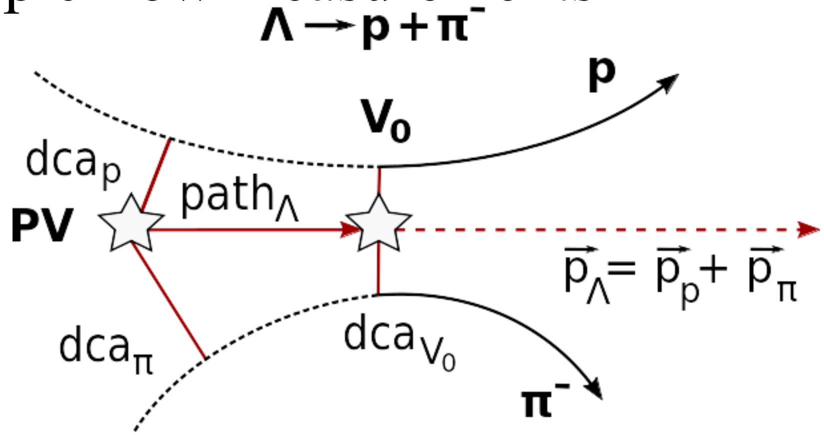
PWG3 activity

There were 8 reports at MPD Cross-PWG since the previous meeting:

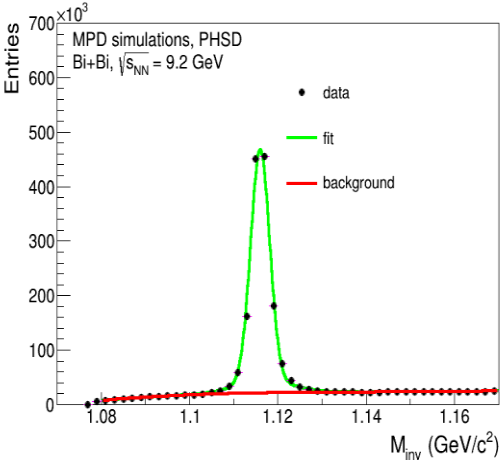
1. D. Prokhorova, *p_T-N fluctuations in terms of strongly intensive variables defined in separated rapidity intervals*, **12 Nov 2024**
2. R.G.F. Mendieta, *Event-by-event strangeness fluctuations*, **12 Nov 2024**
3. P. Parfenov, *Anisotropic flow in MPD-FXT: first look at the production 36,* **18 Feb 2025**
4. P. Parfenov, *Update on the directed and elliptic flow measurements in Xe+W collisions at MPD-FXT,* **18 Mar 2025**
5. G. Eyyubova, *First look at net charge and particle ratio event-by-event dynamical fluctuations with MPD,* **18 Mar 2025**
6. G. Feofilov, *Proton and net-proton High-Order Cumulants: can we do better with MPD at NICA?,* **18 Mar 2025**
7. V. Troshin, *KFParticle for reconstruction of Λ anisotropic flow in the MPD experiment,* **8 Apr 2025**

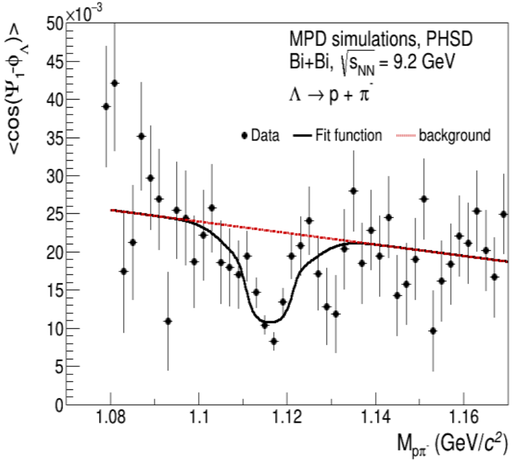
Λ hyperon reconstruction and anisotropic flow measurements

1. Track selection
2. Build Λ from p and π^-
3. Selection of Λ candidates
4. Fitting the m_{inv} distributions
5. Fitting v_n as a function of m_{inv}



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

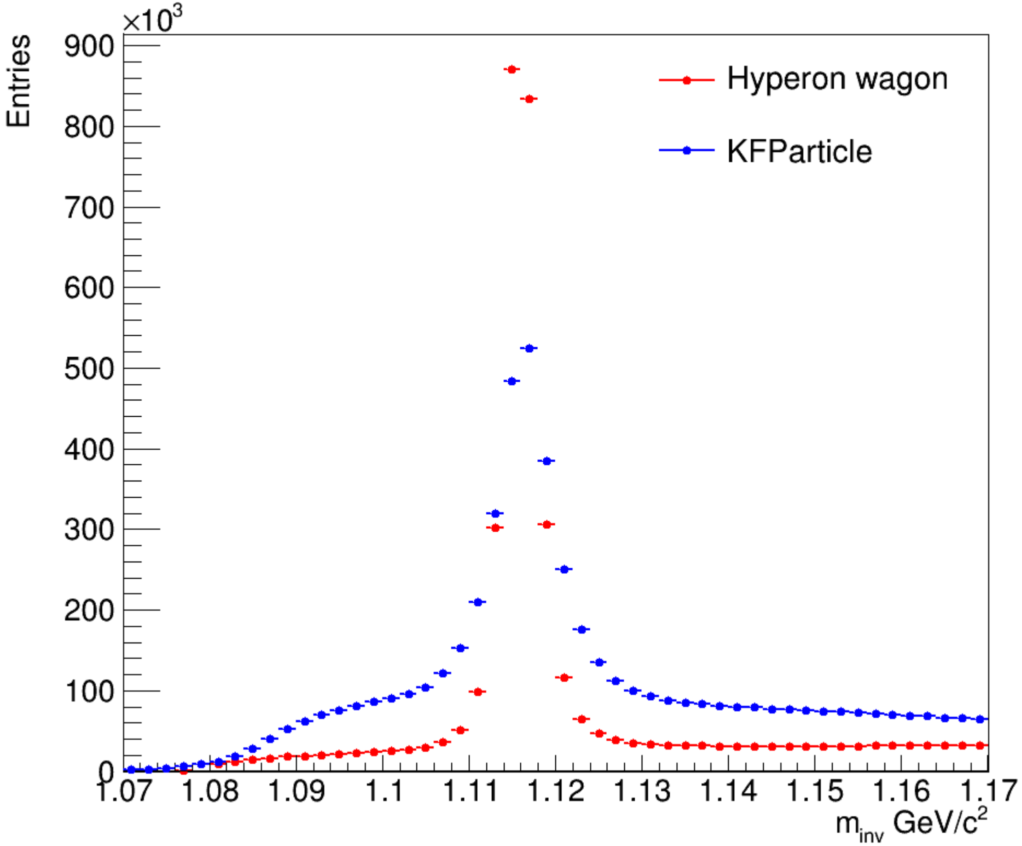




- PV — primary vertex
- V_0 — vertex of hyperon decay
- dca — distance of closest approach
- path — decay length

See V. Troshin's talk

Comparison between MPD Hyperon wagon and KFParticle

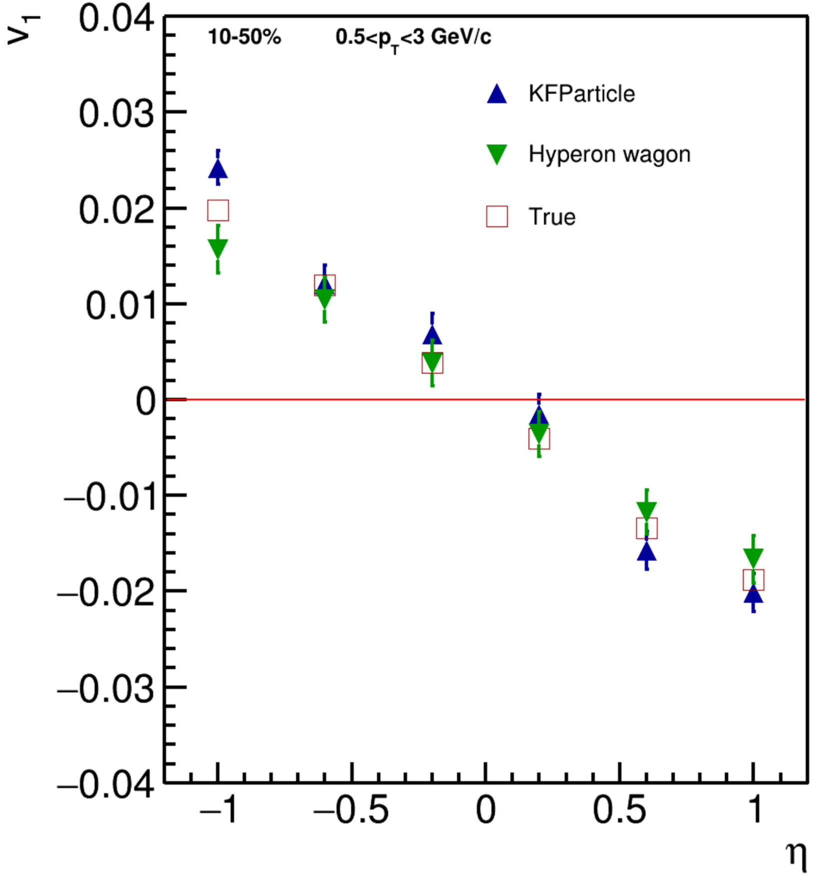


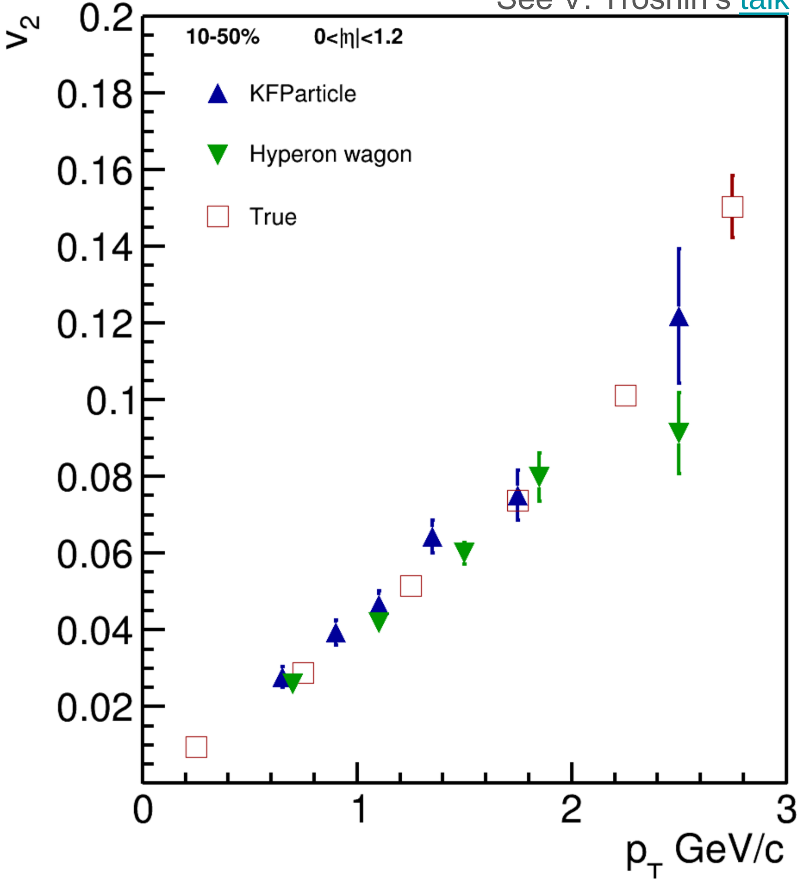
	Hyperon wagon $\omega_2 = \ln \frac{\sqrt{\chi_\pi^2 \chi_p^2}}{\chi_\Lambda^2 + \chi_{V_0}^2}$	KFParticle Plenty of cuts
S/B	12.34	2.11
S	$6.17 \cdot 10^6$	$6.45 \cdot 10^6$
σ	0.002	0.0036

Refit of daughters with mass hypothesis is not conducted in KFParticle at this moment, that might worsen S/B ratio

$v_1(\eta)$ and $v_2(p_T)$ of Λ for Bi+Bi at 9.2 GeV in PHSD model

See V. Troshin's talk

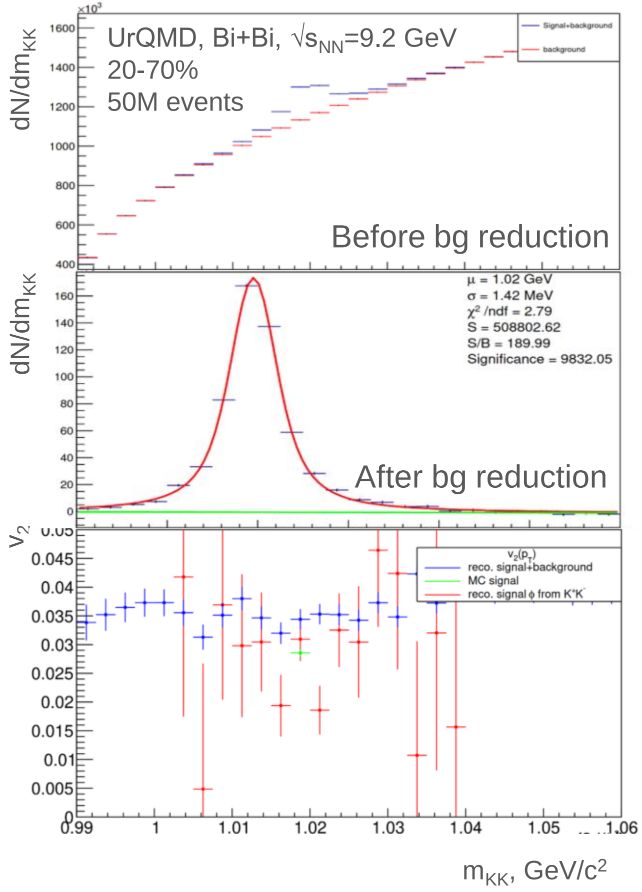


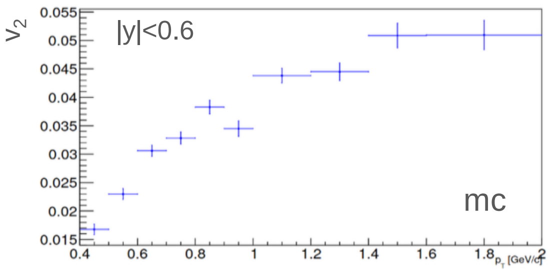


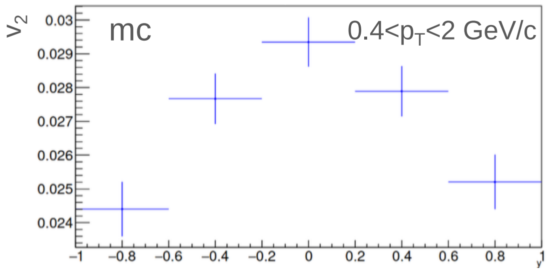
Hyperon wagon and KFParticle provides good agreement with Monte-Carlo and each other

Elliptic flow of φ(1020) meson

See D. Flusova's talk

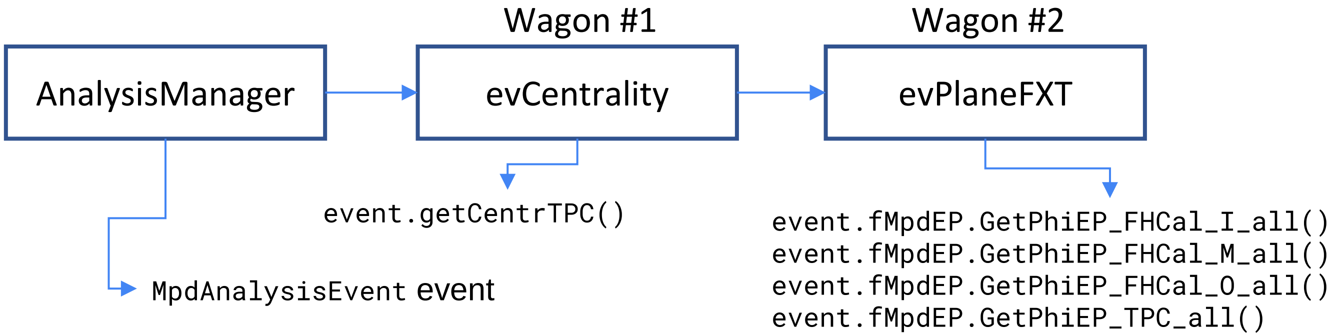


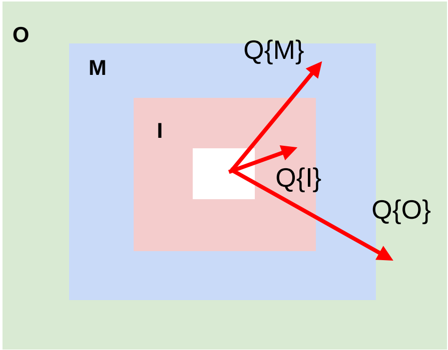




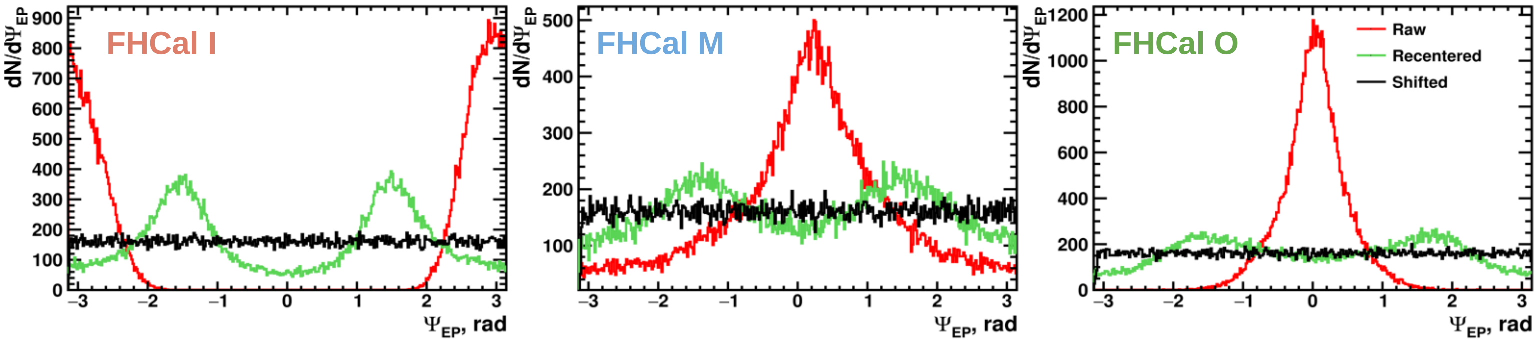
- Wagon for measurements of elliptic flow of φ(1020) meson is under development
- m_{KK} distributions are obtained with background subtraction using mixed event technique
- However, v_2 of φ-mesons and v_2 of background can not be distinguished - m_{inv} fit method is not optimal. Event plane (Δϕ) method with background subtraction will be used.

evPlaneFXT wagon for EP measurements in MPD





UrQMD, Xe+W, T=2.5A GeV



EP corrections are required in case of MPD-FXT

`evPlaneFXT` wagon is implemented into MPD Analysis Framework
It is similar to `evPlane` for MPD-CLD and provided with brief how-to

Flow methods for v_n calculation

Tested in HADES:

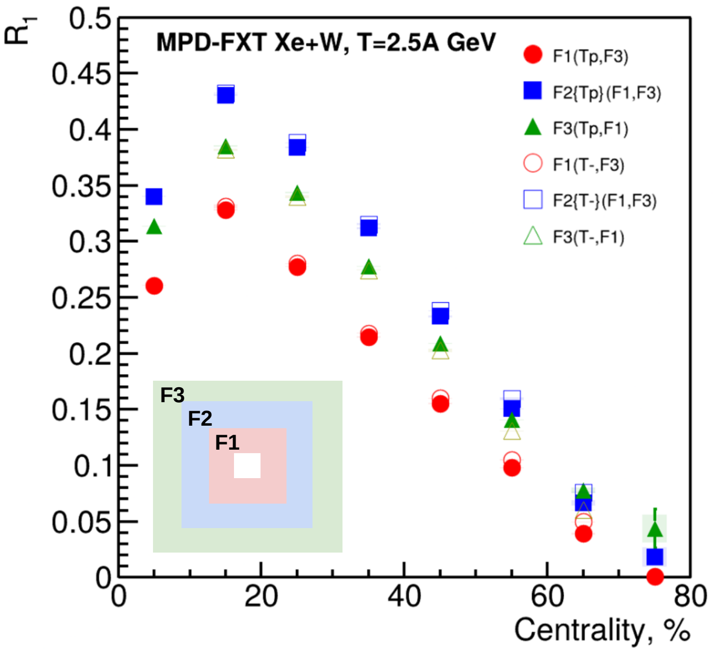
M Mamaev et al 2020 PPNuclei 53, 277–281
M Mamaev et al 2020 J. Phys.: Conf. Ser. 1690 012122

Scalar product (SP) method:

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

Where R_1 is the resolution correction factor

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



Symbol "F2(F1,F3)" means R_1 calculated via (3S resolution):

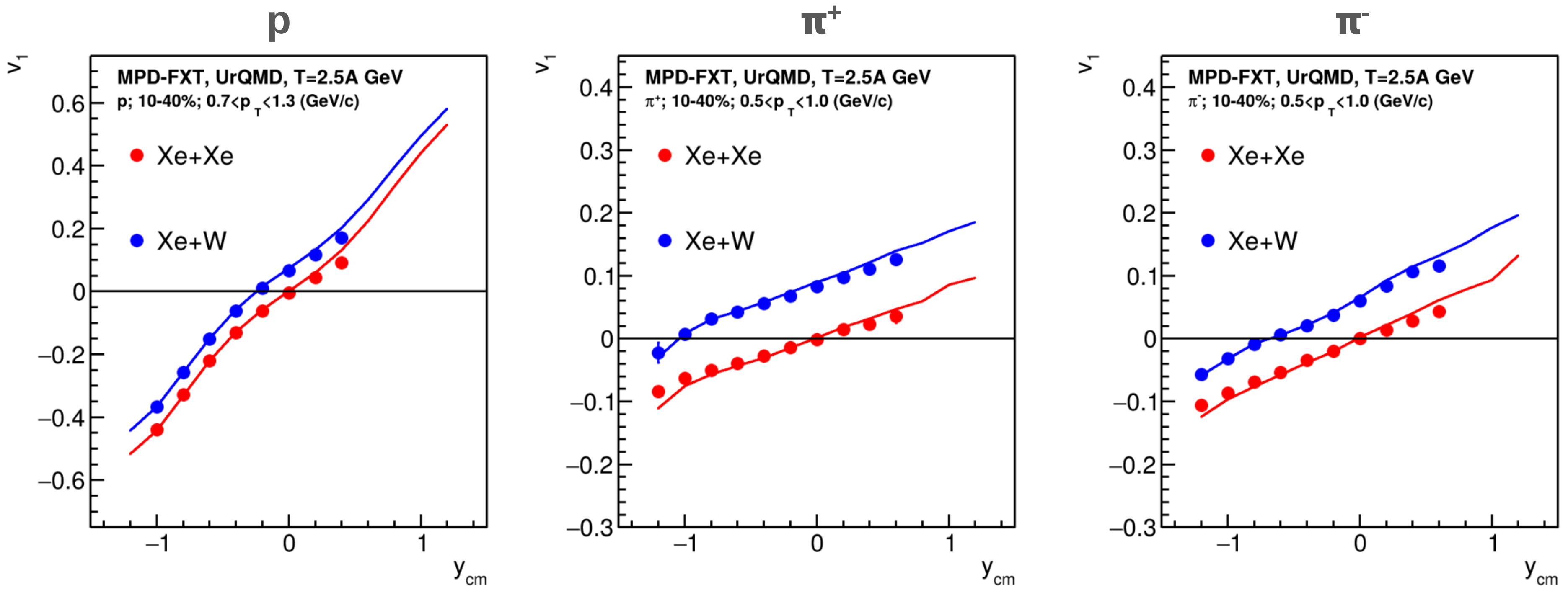
$$R_1^{F2(F1,F3)} = \frac{\sqrt{\langle Q_1^{F2} Q_1^{F1} \rangle \langle Q_1^{F2} Q_1^{F3} \rangle}}{\sqrt{\langle Q_1^{F1} Q_1^{F3} \rangle}}$$

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

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

Results: $v_1(y)$

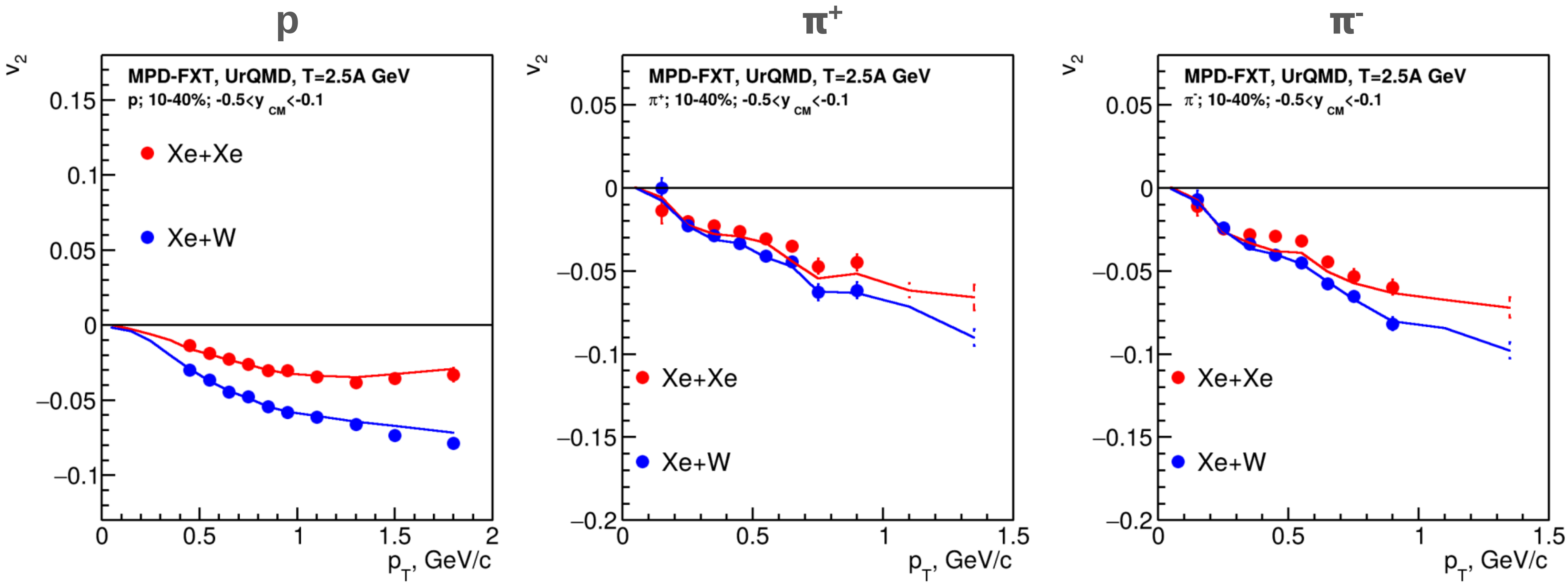
See P. Parfenov's talk



Good overall agreement with mc data

Results: $v_2(p_T)$

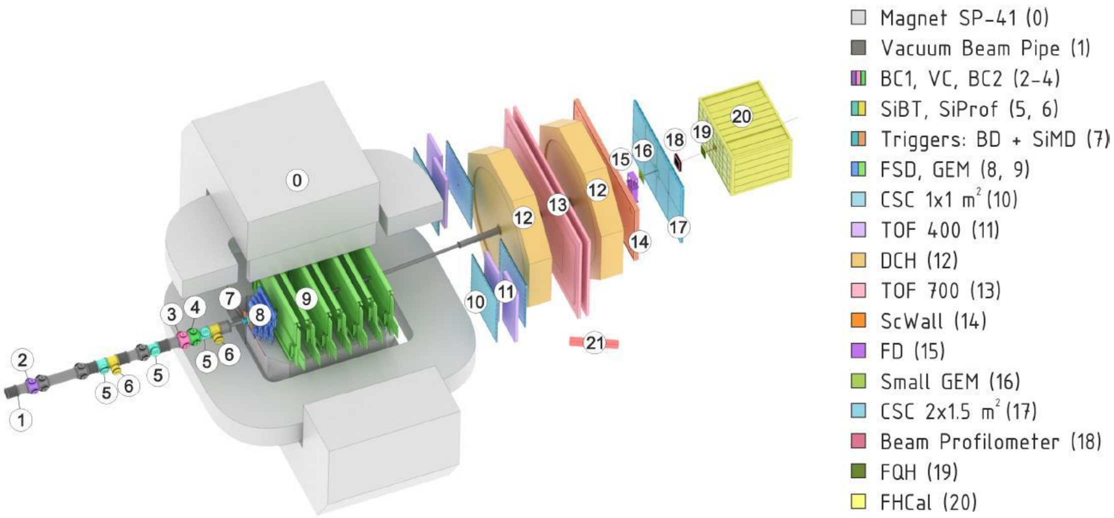
See P. Parfenov's talk



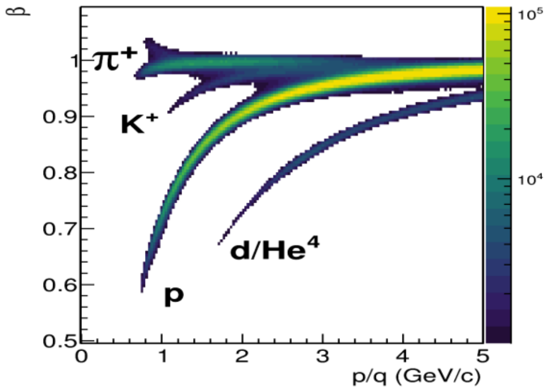
Good overall agreement with mc data

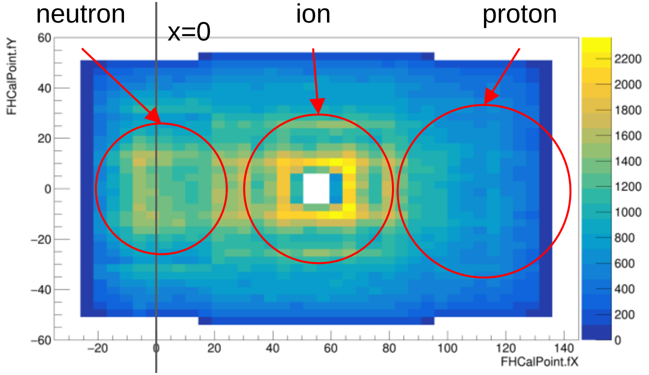
Flow measurements at the BM@N experiment

Xe+CsI collisions at E_{kin}=3.8



Nucl.Instrum.Meth.A 1065 (2024)



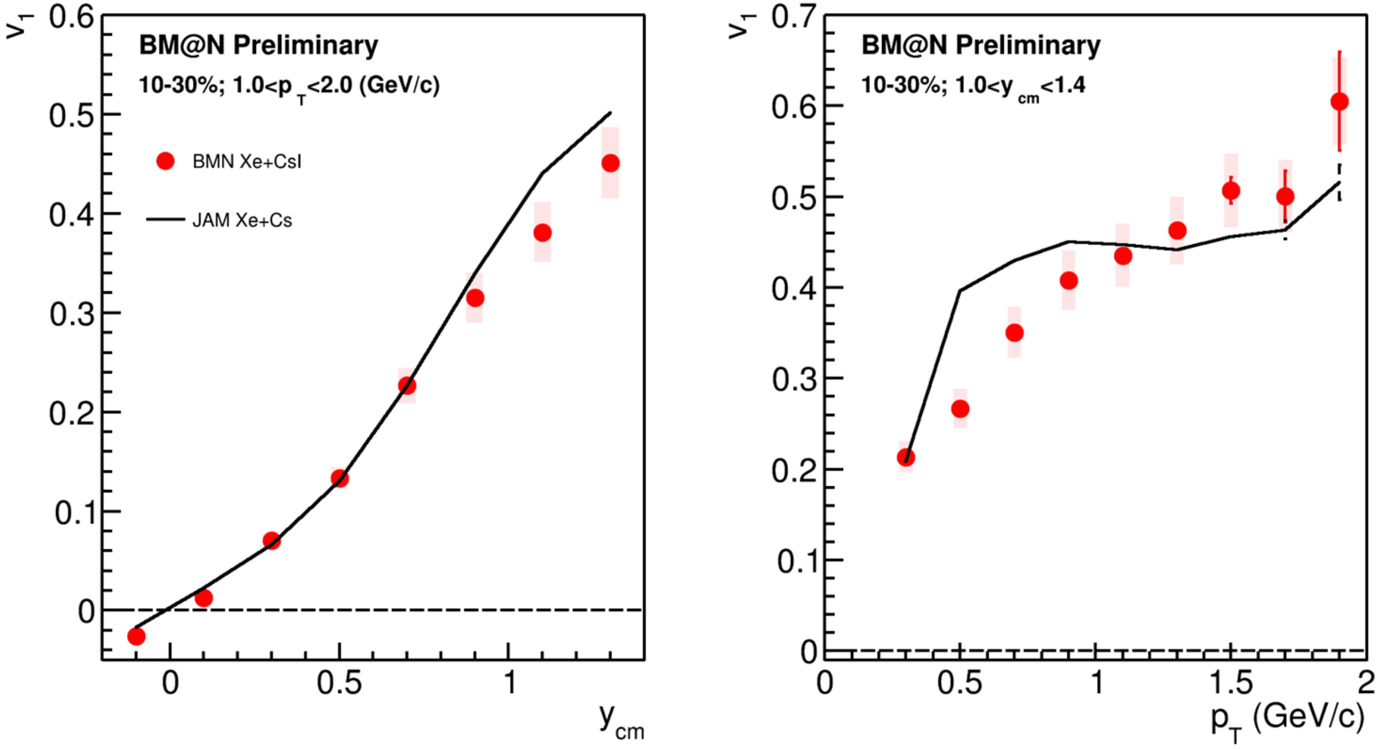


Latest physical run with xenon beam allows us to test analysis techniques on real experimental data

Symmetry plane is measured using sub-events from FHCal and FSD+GEM

$v_1(y_{cm},p_T)$ of protons in Xe+CsI data at E_{kin}=3.8*A* GeV

M. Mamaev, Int.J.Mod.Phys.E 33 (2024) 11, 2441009

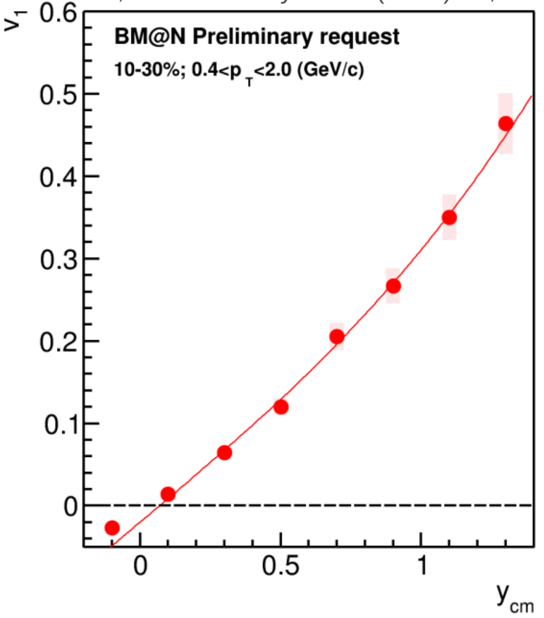


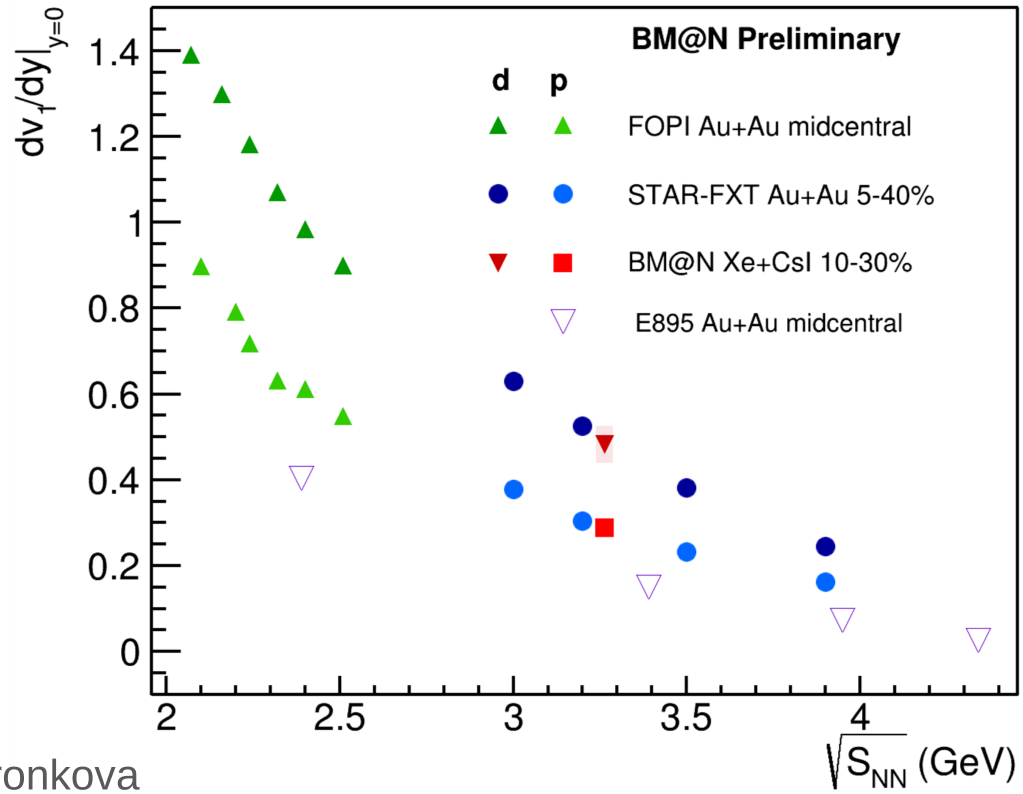
JAM model is within 8% agreement at y_{cm}<1

dv_1/dy of protons in Xe+CsI data at E_{kin}=3.8*A* GeV

M. Mamaev, P. Parfenov, A. Taranenko, Phys.Part.Nucl. 55 (2024) 4, 853-858

M. Mamaev, Int.J.Mod.Phys.E 33 (2024) 11, 2441009





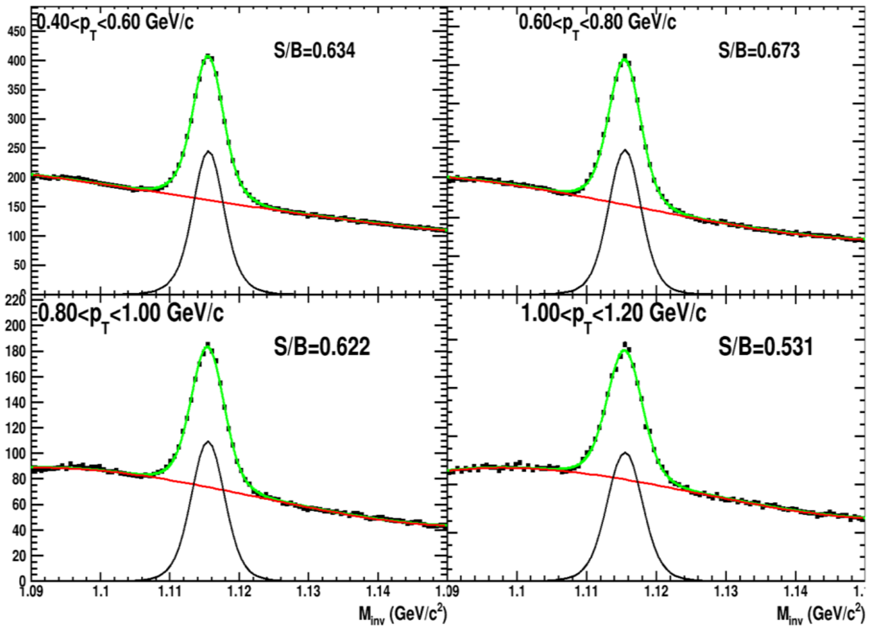
Study of v_1 in the BM@N:

- v_1 of protons - M. Mamaev
- v_1 of light nuclei - M. Mamaev, I.Zhavoronkova

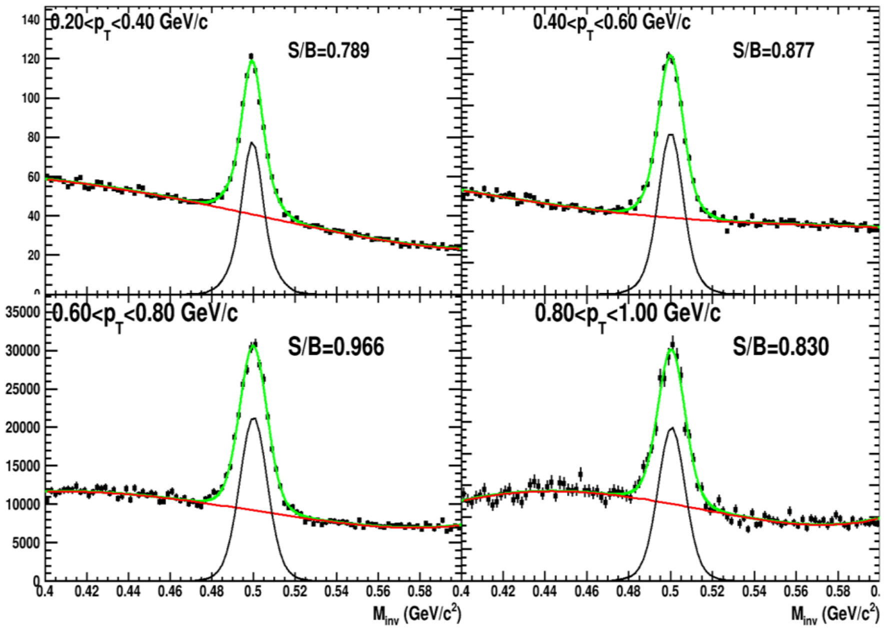
dv_1/dy is in a good agreement with STAR

m_{inv} distributions of Λ and K^0_S in the BM@N Xe+Cs(I) at 3.8A GeV

Λ hyperons



K^0_S mesons

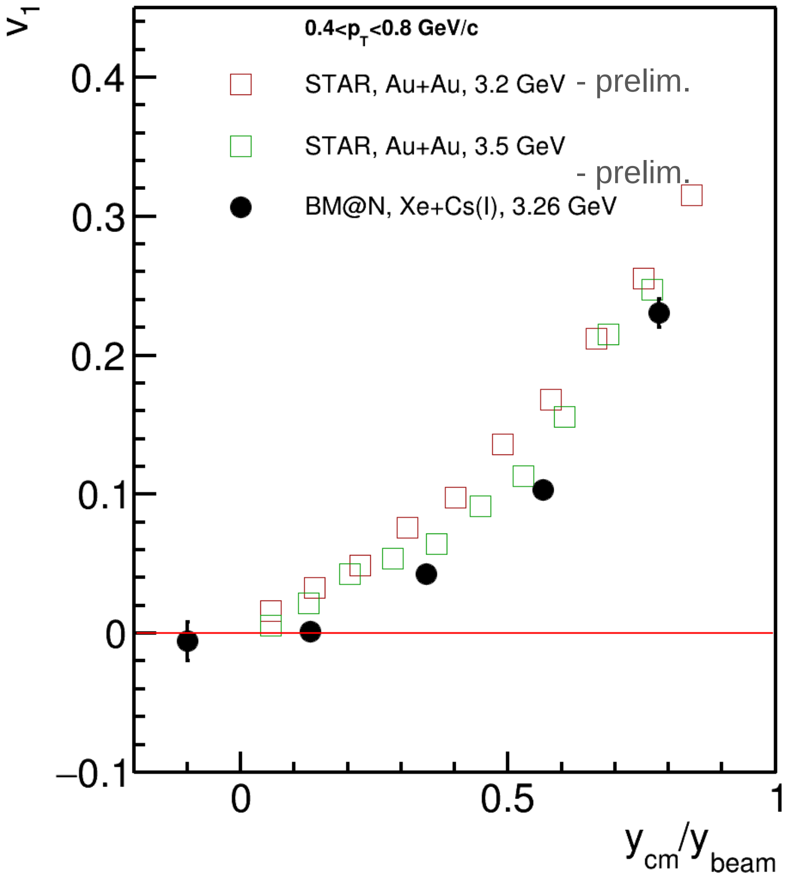


See V. Troshin's talk

KFParticle provides good peak quality in experimental data

$v_1(y)$ of Λ in the BM@N experiment: comparison with STAR

See V. Troshin's talk



Centrality: 5-40%
p_T: 0.4-0.8 GeV/c

The results are systematically lower, maybe because of the difference in system of the collision

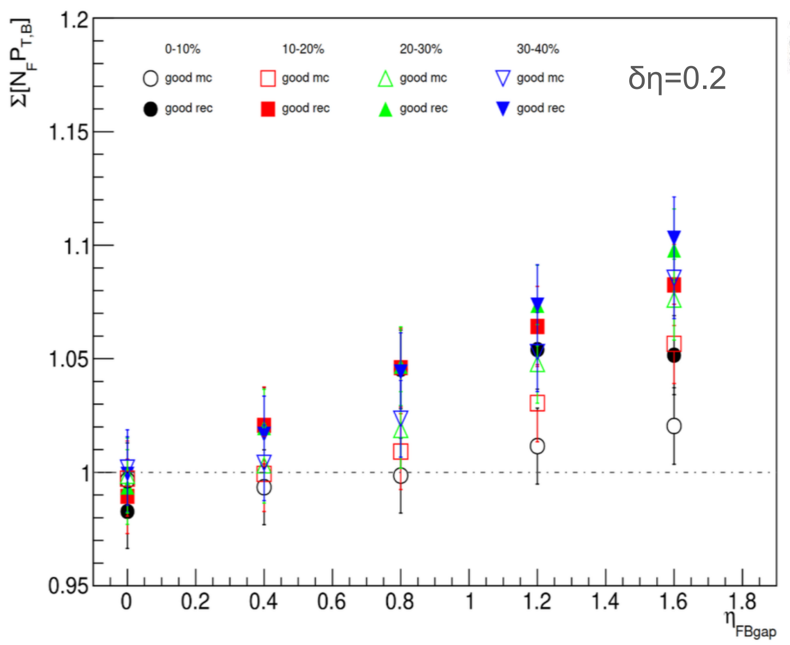
Wagon for measuring p_T-N fluctuations in MPD

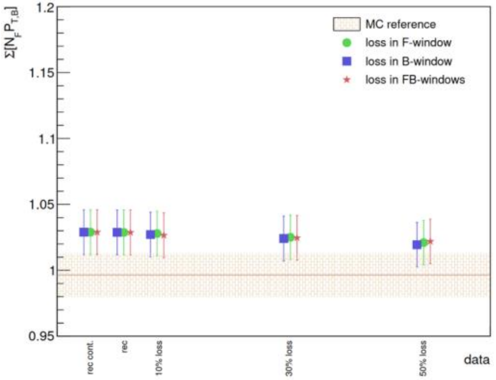
$$\Sigma[N_F, P_{T,B}] = \frac{\langle N_F\rangle \omega[P_{T,B}] + \langle P_{T,B}\rangle \omega[N_F] - 2\cdot \mathrm{cov}(N_F, P_{T,B})}{(\langle N_F\rangle + \langle N_B\rangle)\cdot \overline{p}_{T,B} + \langle N_F\rangle \omega[[p_{T,B}]]}$$

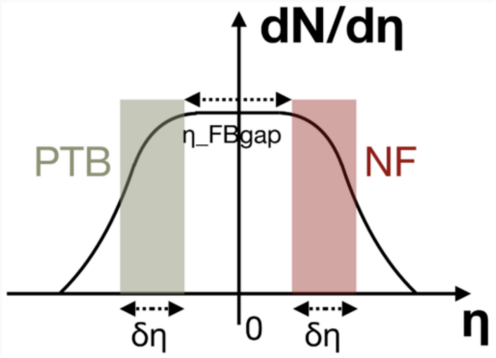
$$\omega[A] = \frac{\langle A^2\rangle - \langle A\rangle^2}{\langle A\rangle}$$

$$\mathrm{cov}(A,B) = \langle AB\rangle - \langle A\rangle\langle B\rangle$$

See D. Prokhorova's talk







- Analysis wagon for studying p_T-N fluctuations is ready for use
- $\Sigma[N_F,p_{T,B}]$ is shown not to be sensitive to the random losses of reconstructed tracks

Analysis of reconstructed UrQMD data shows the possibility to measure $\Sigma[N_F,p_{T,B}]$ in MPD experiment

Event-by-event dynamical fluctuations in MPD

See G. Eyyubova's talk

Fluctuations of conserved quantities (B,S,Q) in a limited phase space probe the QGP phase

Dynamical fluctuation variable $\mathbf{v_{dyn}}$ was introduced (to get rid of statistical fluctuations) which measures deviation from Poisson behavior:

Differentiate partonic vs hadronic state:

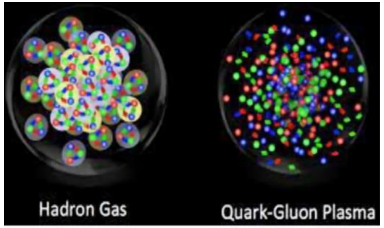
D-measure: $4\frac{\langle \delta Q^2 \rangle}{\langle N_{ch} \rangle}$

$$D = \begin{cases} 4\text{ , HG} \\ 3\text{ , HRG} \\ 1\text{ - }1.5\text{ , QGP} \end{cases}$$

For $\langle N_+ \rangle \approx \langle N_- \rangle$: $D=4\frac{\langle \delta Q^2 \rangle}{\langle N_{ch} \rangle} \approx \langle N_{ch} \rangle \langle v_{dyn} \rangle + 4$

S. Jeon, V. Koch, Phys. Rev. Lett. **85**, 2076
S. Jeon, V. Koch, arXiv:hep-ph/0304012

Fluctuations of total charge $Q \sim q^2$ of sources



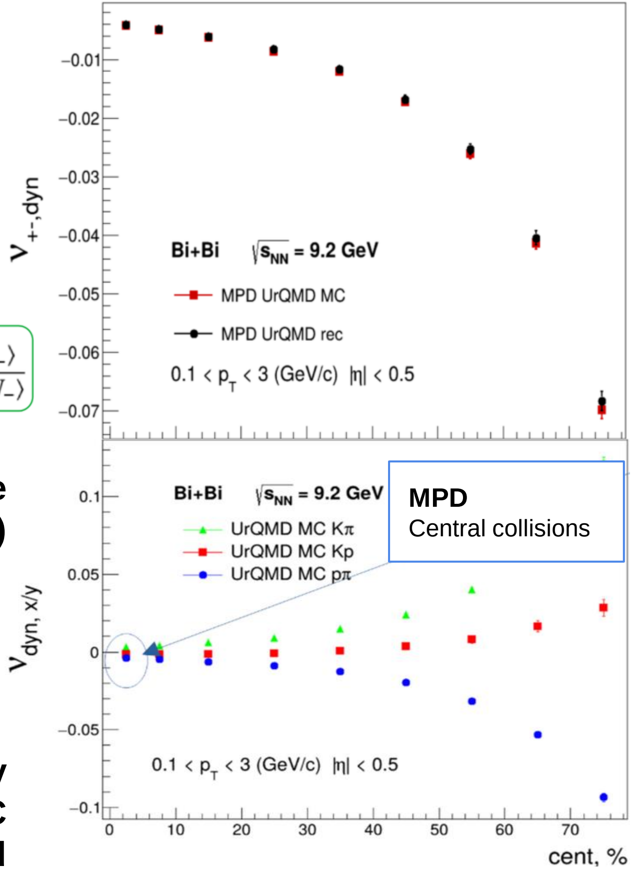
$q^2=1$ $\qquad$ $q^2=1/9,\ 4/9$

$$\nu_{dyn}[+,-] = \frac{\langle N_+(N_+-1)\rangle}{\langle N_+\rangle^2} + \frac{\langle N_-(N_--1)\rangle}{\langle N_-\rangle^2} - 2\frac{\langle N_+N_-\rangle}{\langle N_+\rangle\langle N_-\rangle}$$

Net charge fluctuations were calculated using v (and $\mathbf{vN_{ch}}$) observable in Bi+Bi collisions at 9.2 GeV:

- Good agreement between MC and Reco

Particle ratio fluctuations currently were measured only on the MC level - results from reconstructed data will be included later on



Fluctuations: high-order cumulant measurements in MPD

$$C_1 = \langle \Delta N \rangle, \quad C_2 = \langle (\delta N)^2 \rangle, \quad C_3 = \langle (\delta N)^3 \rangle,$$
$$C_4 = \langle (\delta N)^4 \rangle - 3\langle (\delta N)^2 \rangle^2.$$

$$M = C_1, \quad \sigma^2 = C_2, \quad S = \frac{C_3}{(C_2)^{3/2}}, \quad \kappa = \frac{C_4}{(C_2)^2}$$

See R.G.F. Mendieta's talk

New Centrality Bin Width Correction (CBWC) is proposed to take into account volume fluctuations (CBWC-V):

$M = \langle N \rangle = C_1$, $\rightarrow$ $c1 = M/V^r = \langle N^r/V^r \rangle$,

$\delta N = N - \langle N \rangle$ $\rightarrow$ $\delta N^r = N^r/V^r - \langle N^r/V^r \rangle$

$\sigma^2 = \langle (\delta N)^2 \rangle = C_2$, $\rightarrow$ $c2 = \sigma_r^2 = \langle (\delta N^r)^2 \rangle$,

$S = \langle (\delta N)^3 \rangle / \sigma^3 = C_3/C_2^{3/2}$, $\rightarrow$ $S_r = \langle (\delta N^r)^3 \rangle / \sigma_r^3$,

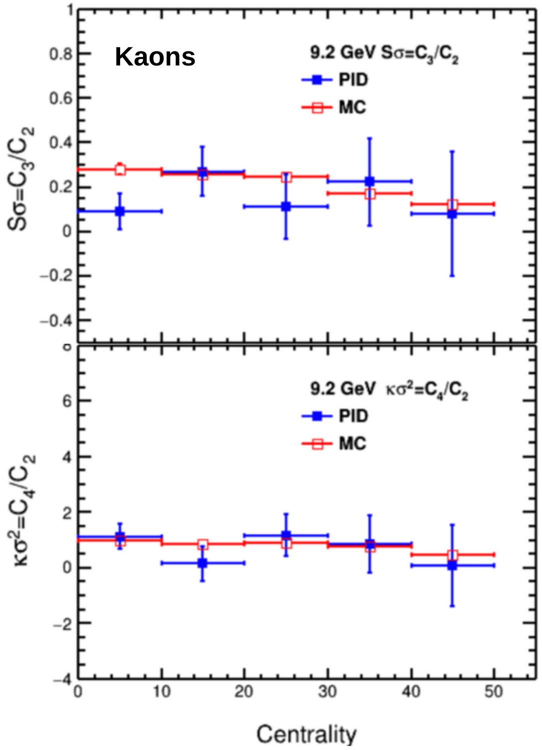
$k = \langle (\delta N)^4 \rangle / \sigma^4 - 3 = C_4/C_2^2$ $\rightarrow$ $k_r = \langle (\delta N^r)^4 \rangle / \sigma_r^4 - 3$

See G. Feofilov's talk

$V^r = \langle N^r_{part} \rangle V_0$

Here a volume factor $V_0 = 2.83\ fm^3$

Phys. Rev. C 88, 034911 (2013)



The study of strangeness number fluctuations and the calculation of the first 4 cumulants were presented at the reconstruction level in the MPD experiment

New CBWC-V corrections and more careful centrality selection might help with the remaining discrepancy (and auto-correlation effects) in the most central collisions for Sσ

Summary and Outlook

- **Feasibility study for anisotropic flow:**
  - KFParticle software was used in the performance study of the v_n of Λ^0 and compared with the current solutions in the MpdRoot
  - Feasibility study for v_n of φ(1020) have been started - current results suggest using event plane (Δϕ) method with background subtraction
  - evPlaneFXT wagon for EP measurements in MPD-FXT is ready for use
  - v_n of p and $\pi^{\pm}$ for Xe+W, Xe+Xe at T = 2.5A GeV is shown to have a good agreement between reconstructed and generated data
- **Last xenon run at BM@N allows us to test analysis techniques for flow measurements on real experimental data:**
  - Results for v_1 of p and d are consistent with the world data
  - Measurements for v_1 of Λ^0 and K^0_S using KFParticle package are in progress but results are promising
- **Performance studies of fluctuations:**
  - Analysis wagon for studying p_T-N fluctuations is ready for use and $\Sigma[N_F,p_{T,B}]$ shows small sensitivity to efficiency losses due to track reconstruction
  - Dynamical fluctuation variable v_{dyn} measured with reconstructed data is consistent with the signal from the model
  - During the E-b-E strangeness fluctuations studies, cumulants were measured and were shown to be mostly consistent with the event generator - new corrections and analysis techniques were proposed to correct for existing biases (volume fluctuations, auto-correlation effects, etc.)

Thank you for your attention!

Backup slides

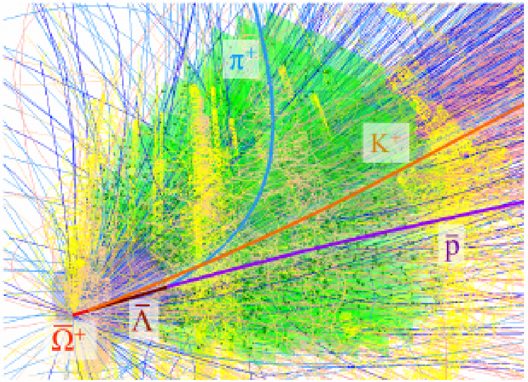
KFParticle formalism

Particles in heavy-ion collision:

STAR

ALICE

CBM



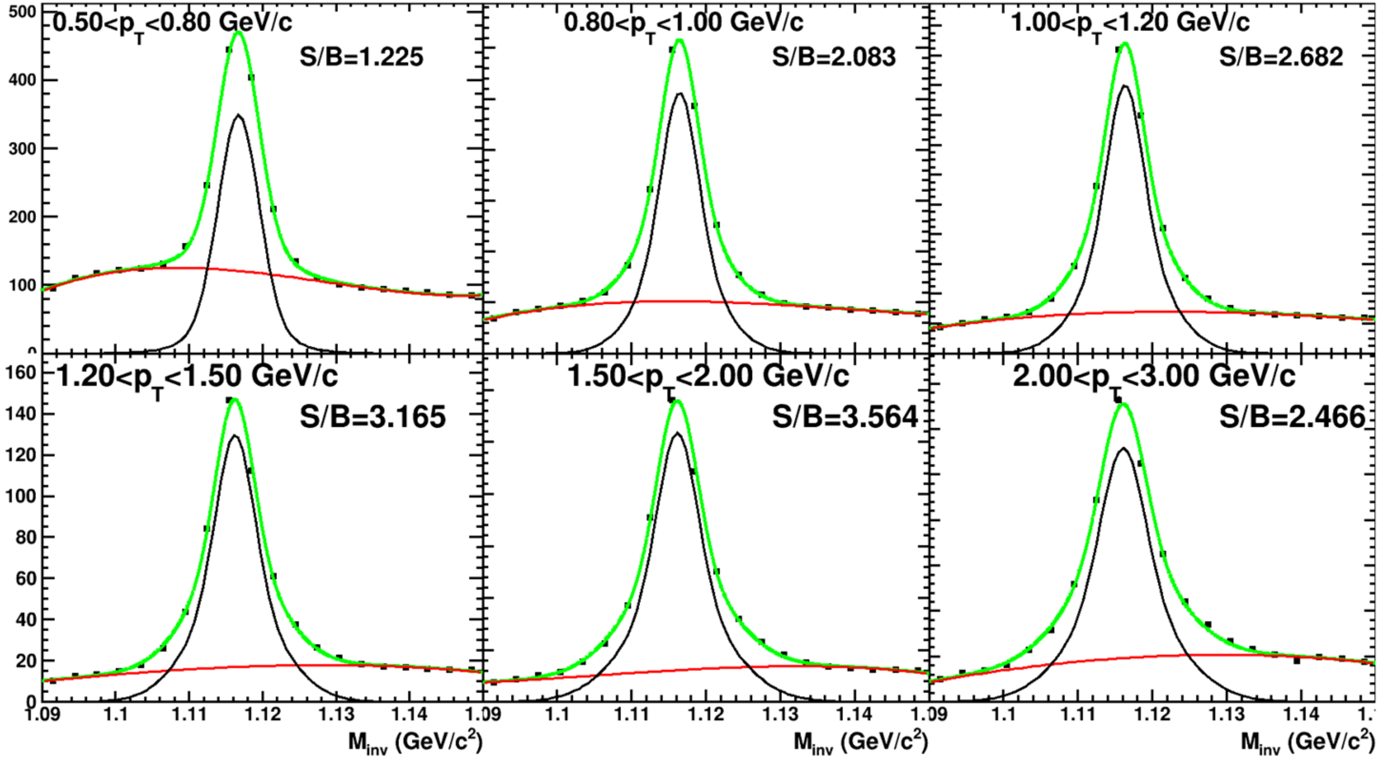
KFParticle:

- developed for complete reconstruction of short-lived particles with their P, E, m, $c\tau$, L, Y

Main benefits:

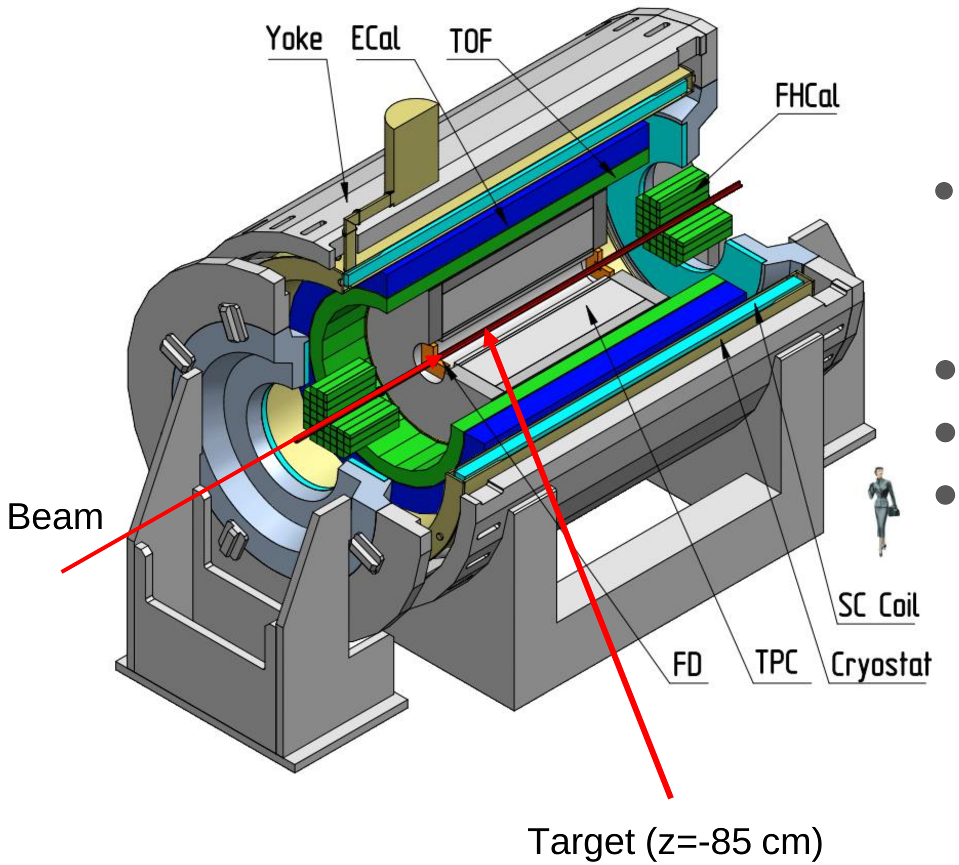
- based on the Kalman filter mathematics
- idependent in sense of experimental setup (collider, fixed target)
- allows one reconstruction of decay chains (cascades)
- daughter and mother particles are described and considered the same way
- daughter particles are added to the mother particle independently

Fitting the m_{inv} distributions of Λ in p_T bins



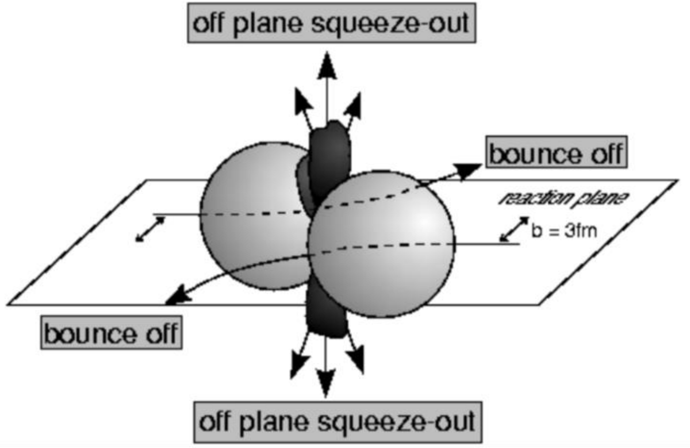
Fitted by 2 gaus functions + 5-degree polynomial
Good fit quality for all bins

MPD in Fixed-Target Mode (FXT)



- Model used: UrQMD mean-field
  - Xe+Xe, E_{kin}=2.5 AGeV ($\sqrt{s_{NN}}$ =2.87 GeV)
  - Xe+W, E_{kin}=2.5 AGeV ($\sqrt{s_{NN}}$ =2.87 GeV)
- Point-like target
- GEANT4 transport
- Particle species selection via TPC and TOF

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

Flow vectors

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

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

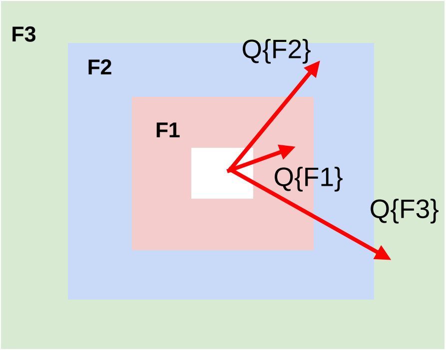
where φ is the azimuthal angle

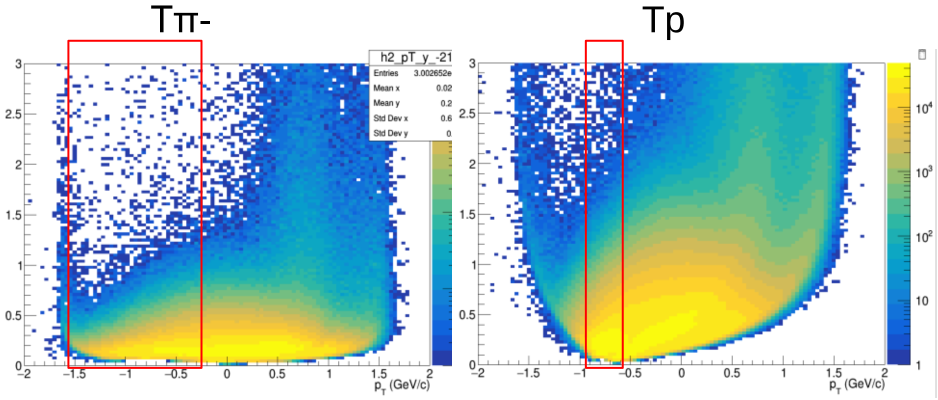
Sum over a group of u_n-vectors in one event forms Q_n-vector:

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

Ψ_n^{EP} is the event plane angle

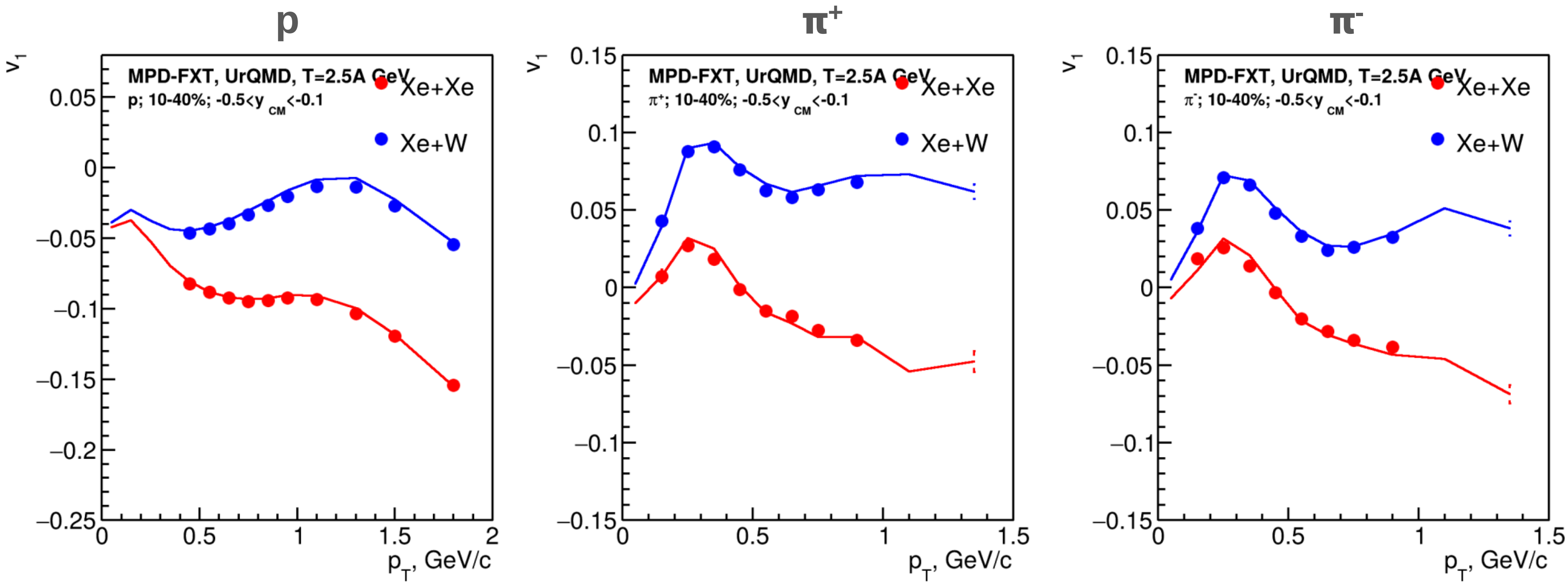
Modules of FHCal divided into 3 groups





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

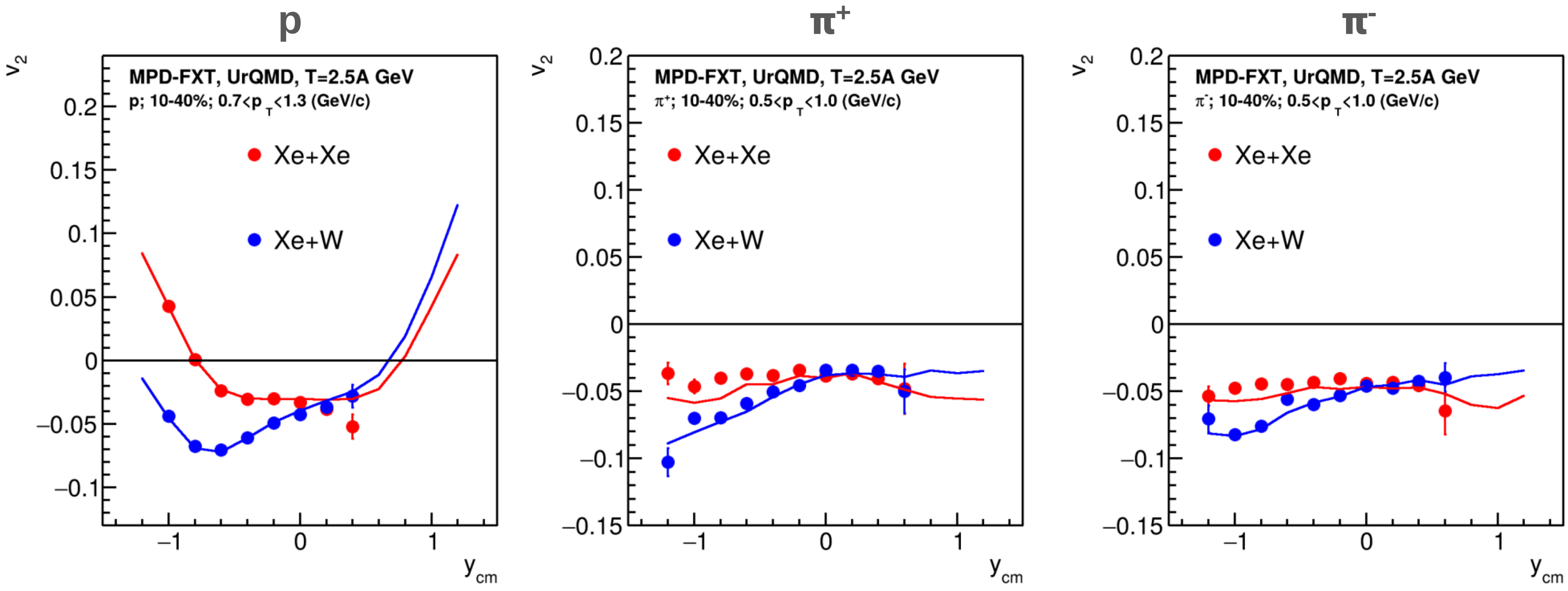
Results: $v_1(p_T)$



Good overall agreement with mc data

Results: $v_2(y)$

Systematics: xxx, xyy



Good overall agreement with mc data