Anisotropic collective flow at Nuclotron/NICA energies

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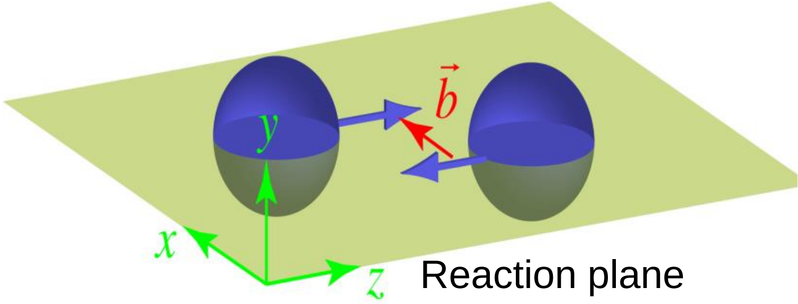
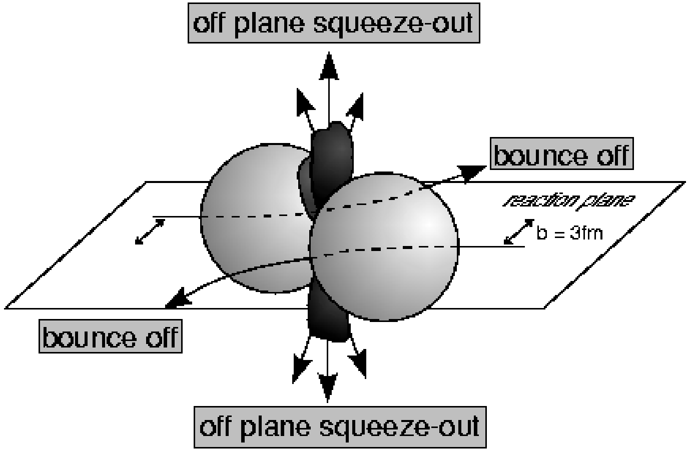
CONFERENCE ON HIGH ENERGY PHYSICS, AANL, Yerevan , Armenia, September 11-14, 2023

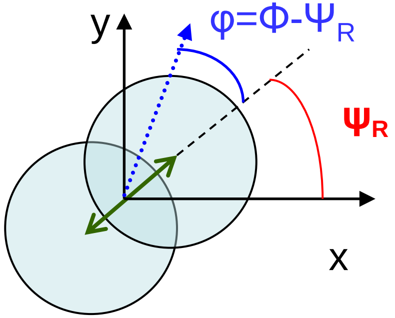
"Squeeze-Out" - First Elliptic flow signal in HIC

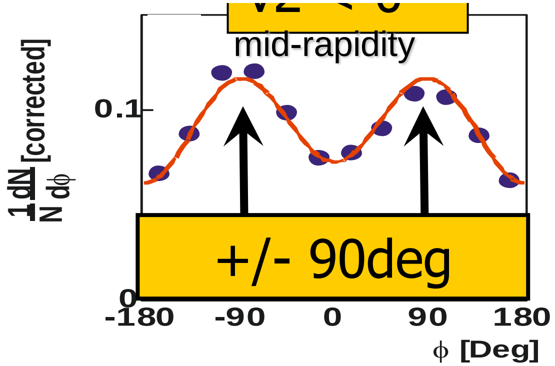
Diogene, M. Demoulins et al., Phys. Lett. B241, 476 (1990)

Plastic Ball, H.H. Gutbrod et al., Phys. Lett. B216, 267 (1989)

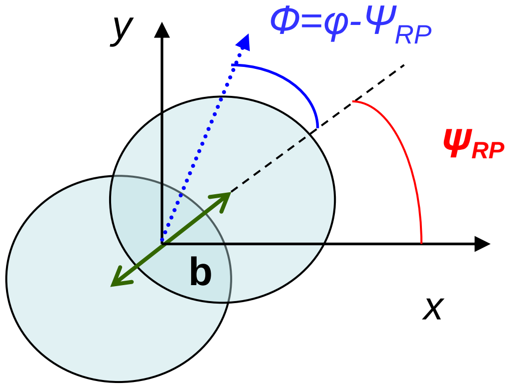






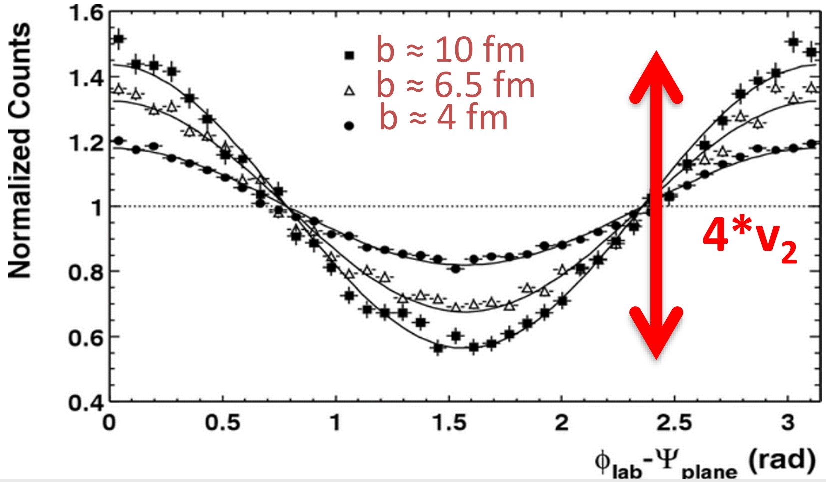


Azimuthal anisotropy of particles at HIC



Sergei Voloshin, Y. Zhang, Z. Phys. C70,(1996), 665

STAR, PRL**90** 032301 (2003)



$$\frac{dN}{d(\varphi-\Psi_{RP})}=\frac{N_0}{2\pi}\left(1+2v_1\cos(\varphi-\Psi_{RP})+2v_2\cos\left(2(\varphi-\Psi_{RP})\right)+....\right)$$

- ❑ The sinus terms are skipped by symmetry arguments
- ❑ From the properties of Fourier's series one has

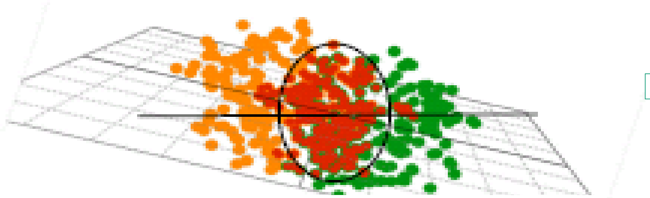
$$v_n=\left\langle\cos\left[n(\varphi-\Psi_{RP})\right]\right\rangle$$

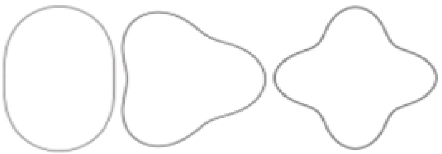
- ❑ Fourier coefficients $\mathbf{V_n}$ quantify anisotropic flow:

v_1 is directed flow, v_2 is elliptic flow, v_3 is triangular flow, etc.

Term “flow” does not mean necessarily “hydro” flow – used only to emphasize the collective behavior of particles in event or multiparticle azimuthal correlation

Anisotropic Flow at RHIC-LHC



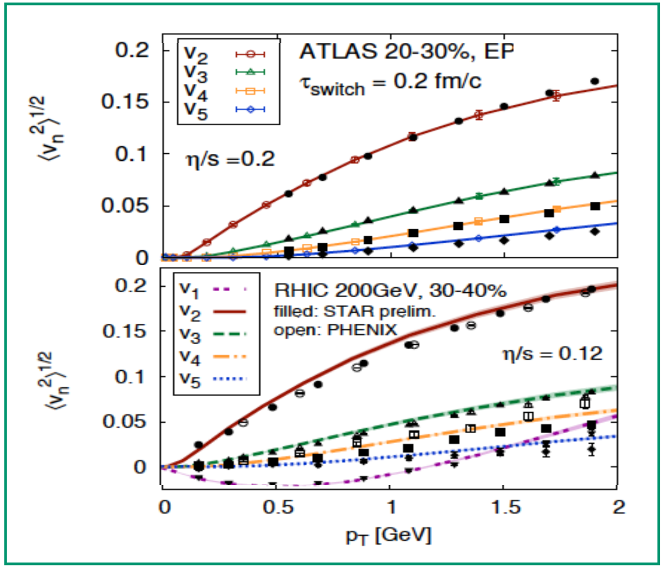


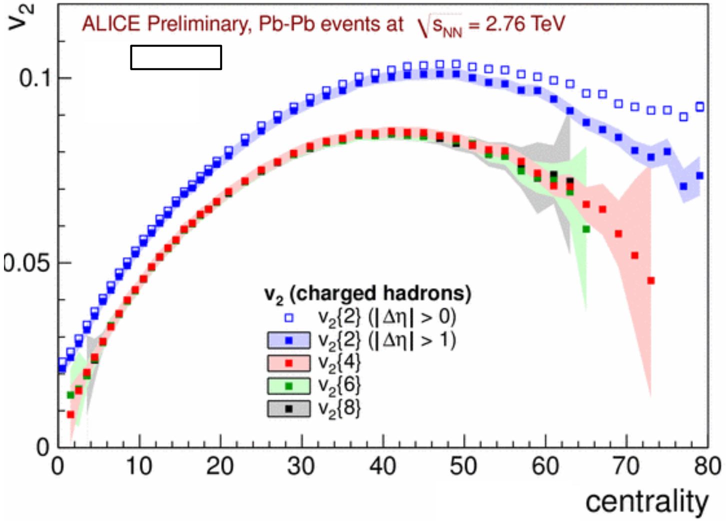
$$\epsilon_n = \sqrt{\frac{\langle r^n \cos n\phi\rangle + \langle r^n \sin n\phi\rangle}{\langle r^n\rangle}}$$

$$\frac{dN}{d\phi} \propto \left(1 + 2\sum_{n=1} v_n \cos\left[n\left(\phi - \Psi_n\right)\right]\right)$$

Initial eccentricity (and its attendant fluctuations) ε_n drive momentum anisotropy v_n with specific viscous modulation

Gale, Jeon, et al., Phys. Rev. Lett. 110, 012302

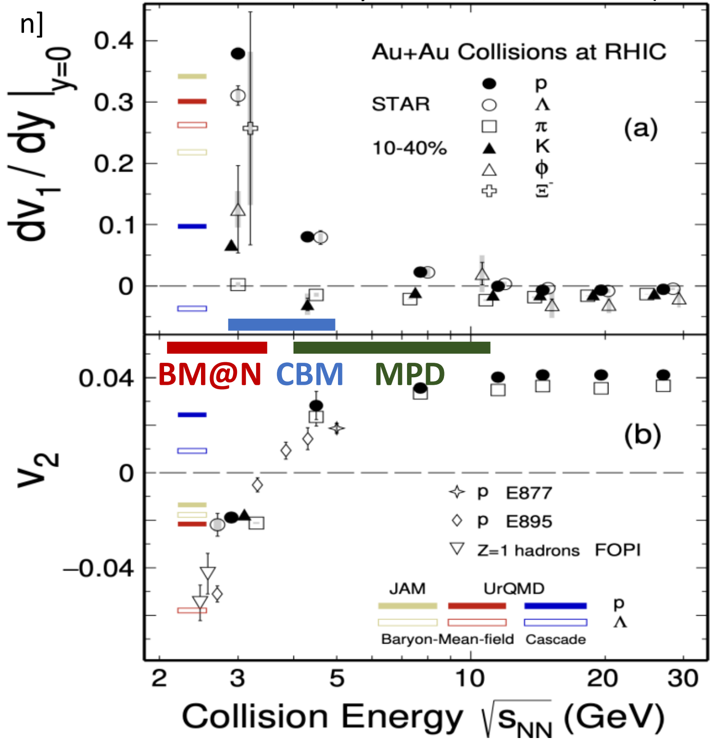


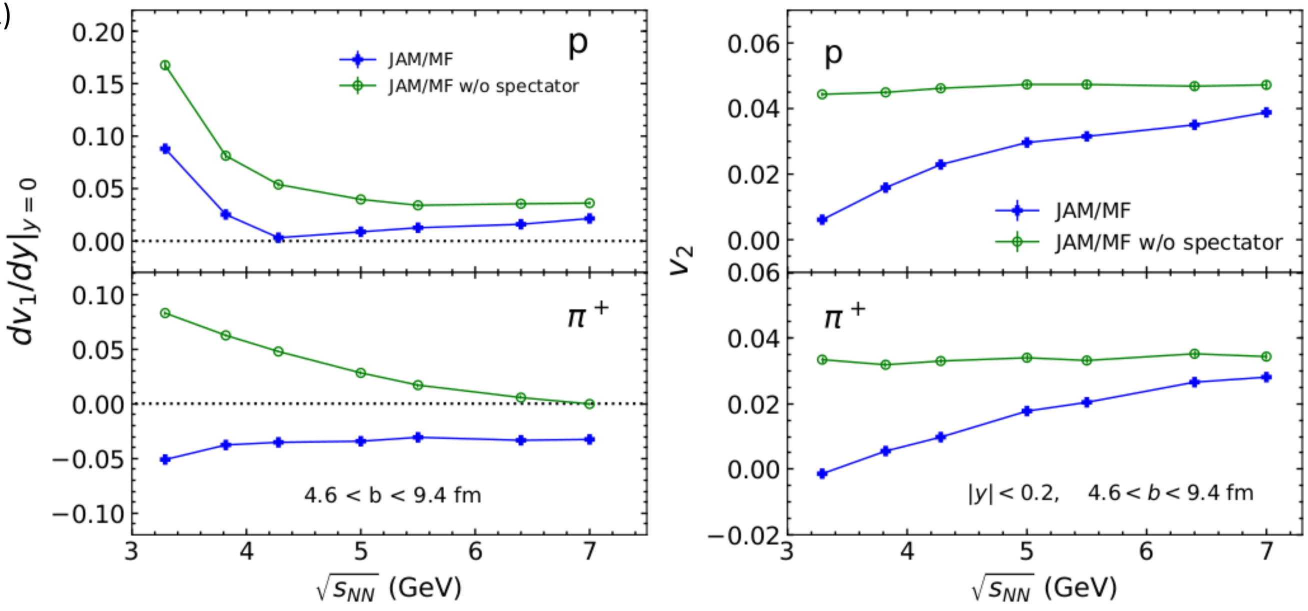


Flow and non-Flow, Fluctuations

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

M. Abdallah et al. STAR, Phys. Lett. B 827, 137003 (2022)





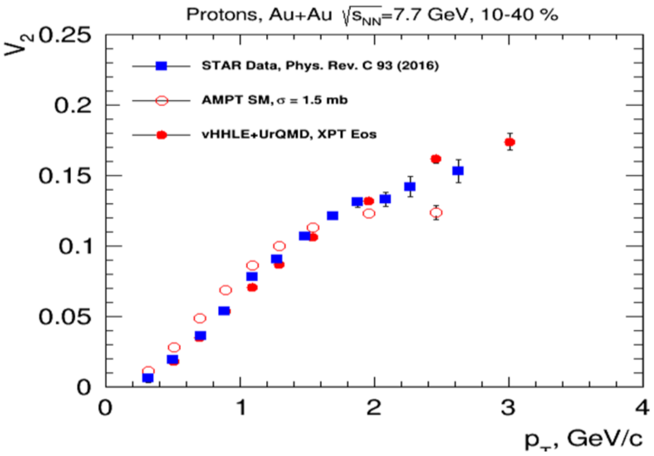
Phys. Rev. C 97, 064913 (2018)

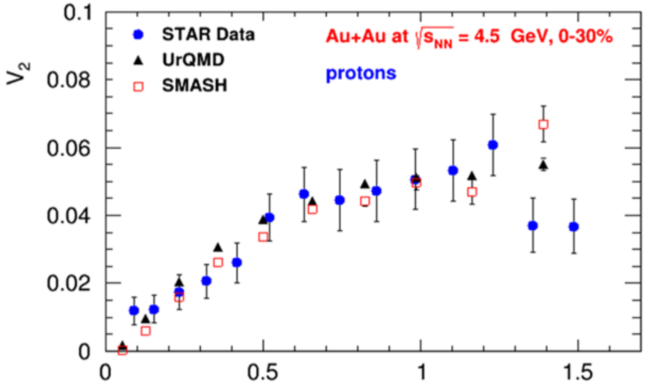
Anisotropic flow at FAIR/NICA energies is a delicate balance between:

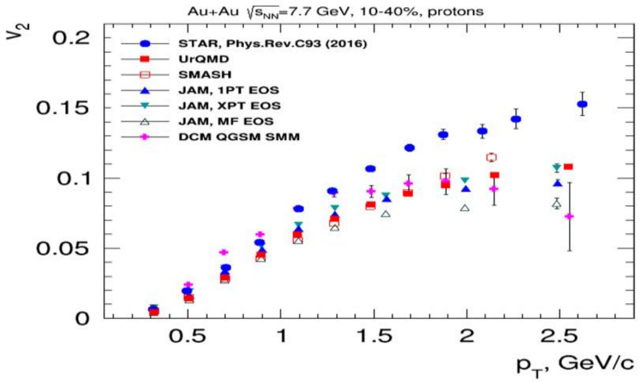
I. The ability of pressure developed early in the reaction zone ($t_{exp} = R/c_s\,, c_s = c\sqrt{dp/d\varepsilon}$) and

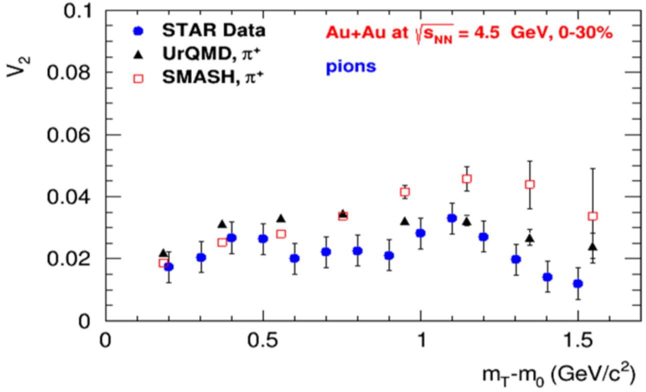
II. The passage time for removal of the shadowing by spectators ($t_{pass} = 2R/\gamma_{CM}\beta_{CM}$)

Elliptic Flow (v_2) at NICA energies: Models vs Data





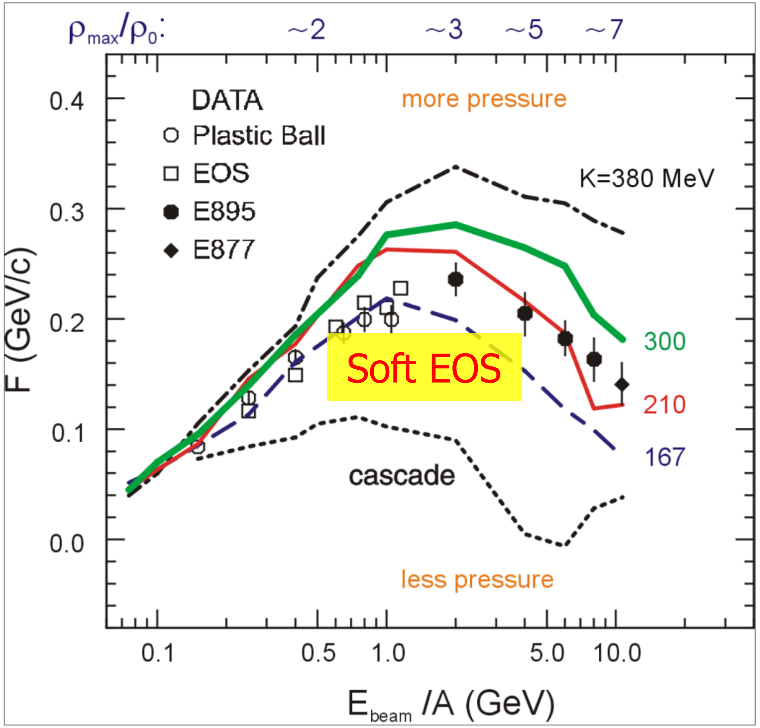


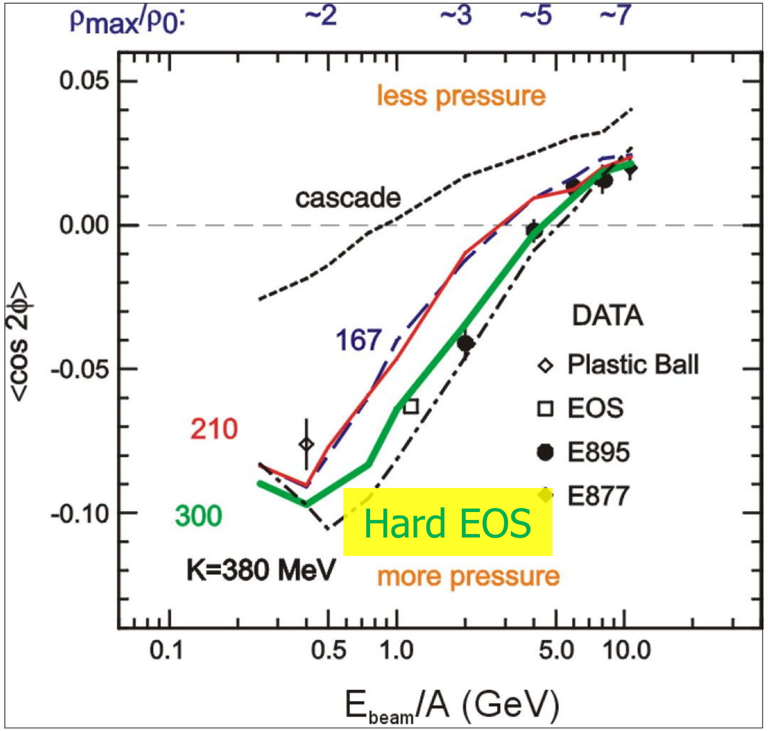


at $\sqrt{s_{NN}} \geq 7.7$ GeV pure string/hadronic cascade models underestimate v_2 – need hybrid models with QGP phase (vHLLE+UrQMD, AMPT with string melting,...) at $\sqrt{s_{NN}} \geq 3$-4.5 GeV pure hadronic models give similar v_2 signal compared to STAR data

Nuclear incompressibility from collective proton flow

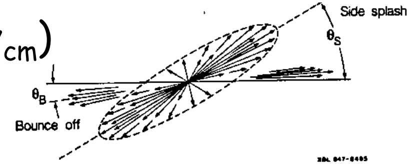
P. Danielewicz, R. Lacey, W.G. Lynch, Science 298 (2002) 1592



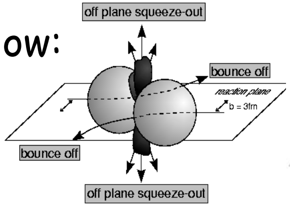


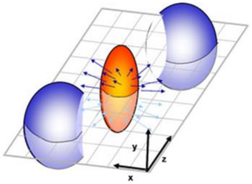
Transverse in-plane flow:

$F = d(p_x/A)/d(y/y_{cm})$



Elliptic flow:

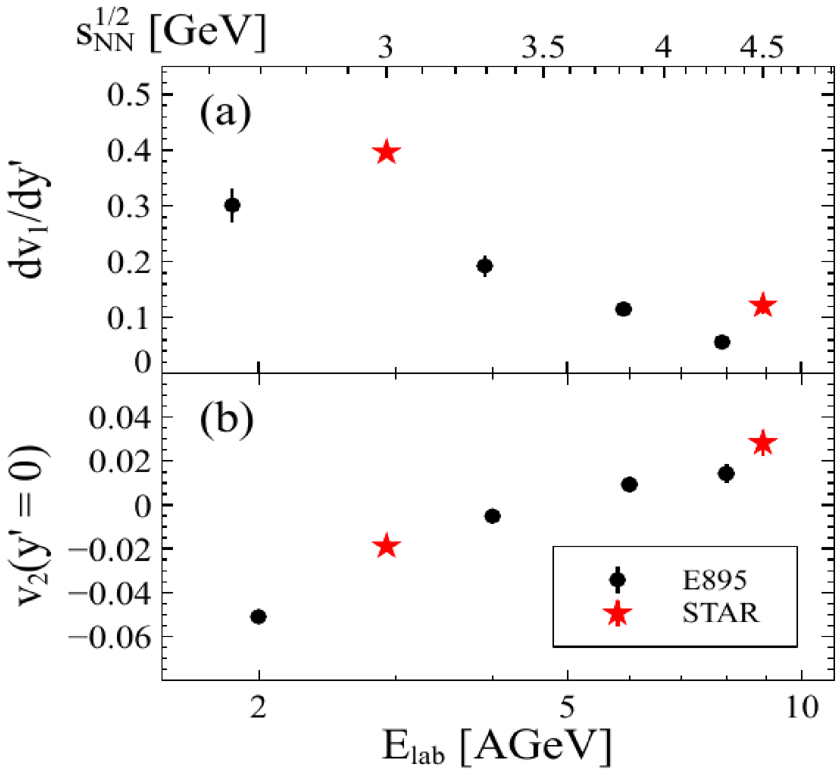


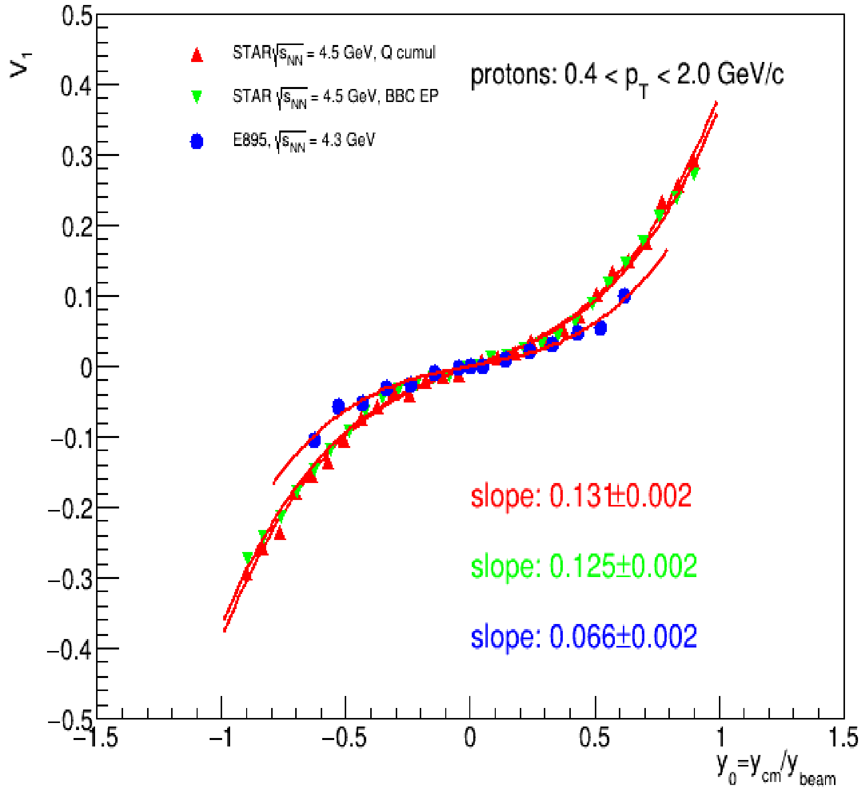


$dN/d\Phi \propto (1 + 2v_1 \cos\Phi + 2v_2 \cos 2\Phi)$

Sensitivity of Au+Au collisions to the symmetric nuclear matter equation of state at 2–5 nuclear saturation densities

Dmytro Oliinychenko,[1,*] Agnieszka Sorensen,[1,†] Volker Koch,[2] and Larry McLerran[1]
[1] Institute for Nuclear Theory, University of Washington, Box 351550, Seattle, Washington 98195, USA
[2] Lawrence Berkeley National Laboratory, 1 Cyclotron Road, Berkeley, California 94720, USA





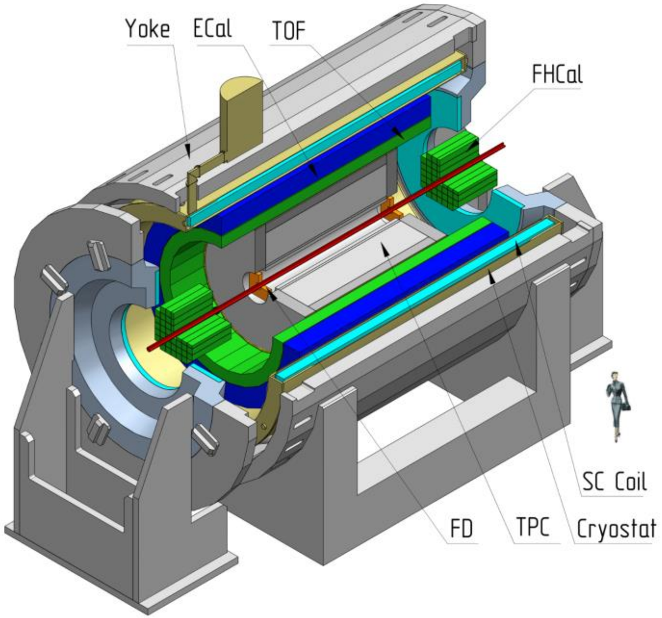
The main source of existing systematic errors in v_n measurements is the difference between results from different experiments (for example, FOPI and HADES, E895 and STAR)

MPD Experiment at NICA

UrQMD → GEANT4 → Reconstruction → Flow analysis

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

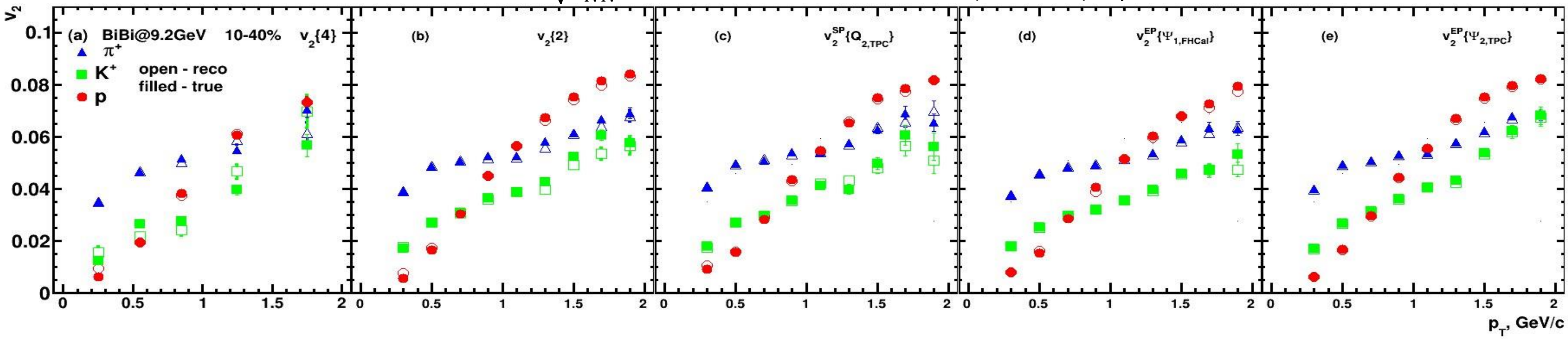
$-5<\eta<-2$	$-1.5<\eta<1.5$	$2<\eta<5$
FHCal	TPC $0.2<p_T<3$ GeV/c	FHCal

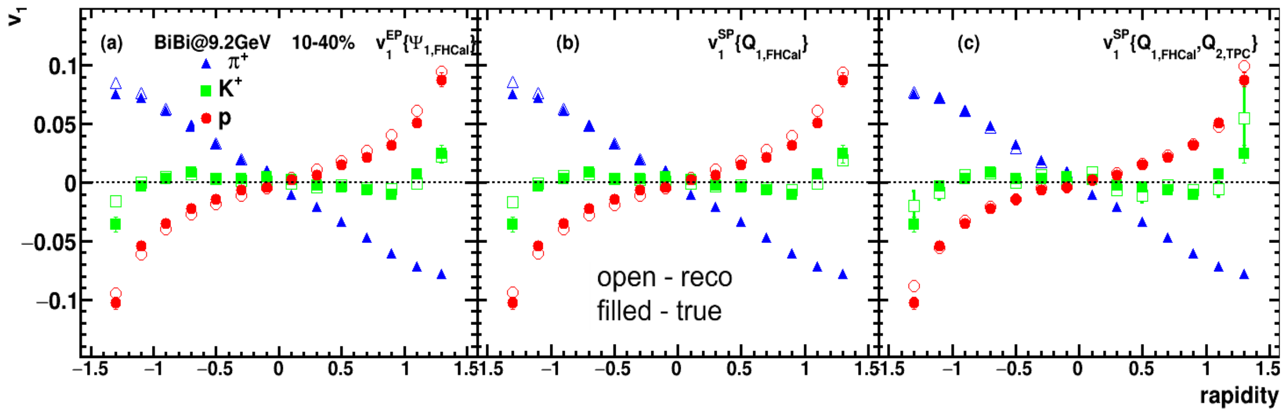


Multi-Purpose Detector (MPD) Stage 1

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

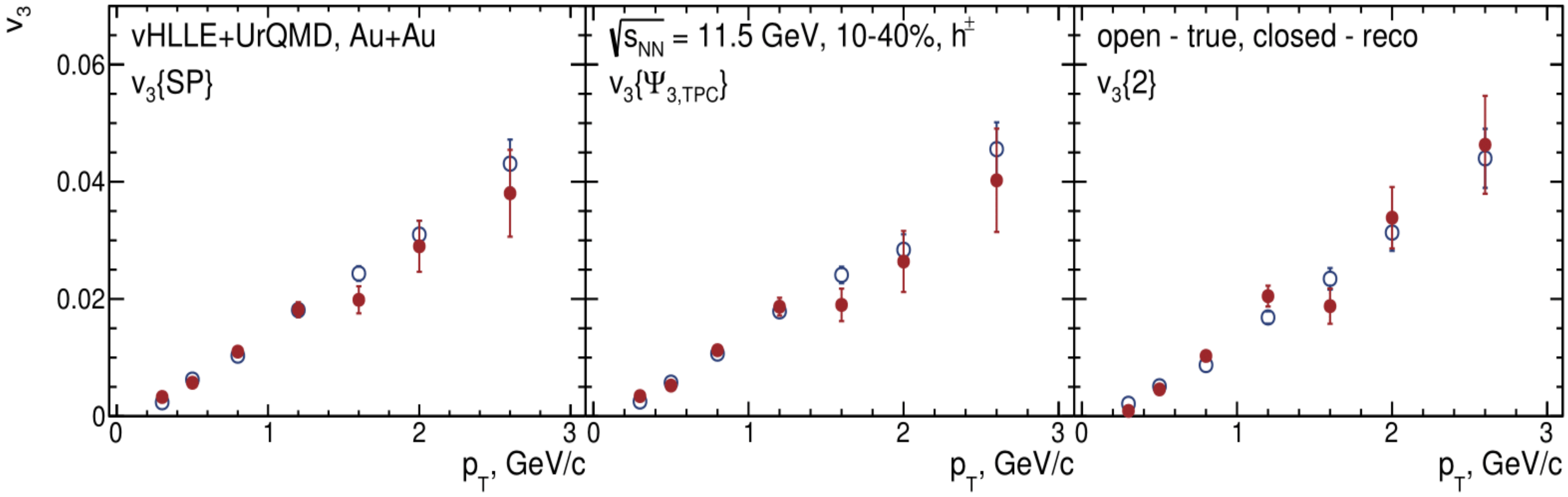
UrQMD, Bi+Bi, $\sqrt{s_{NN}}$=9.2, 10-40%, reconstructed (GEANT4) – production 25





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

Triangular flow with MPD at NICA

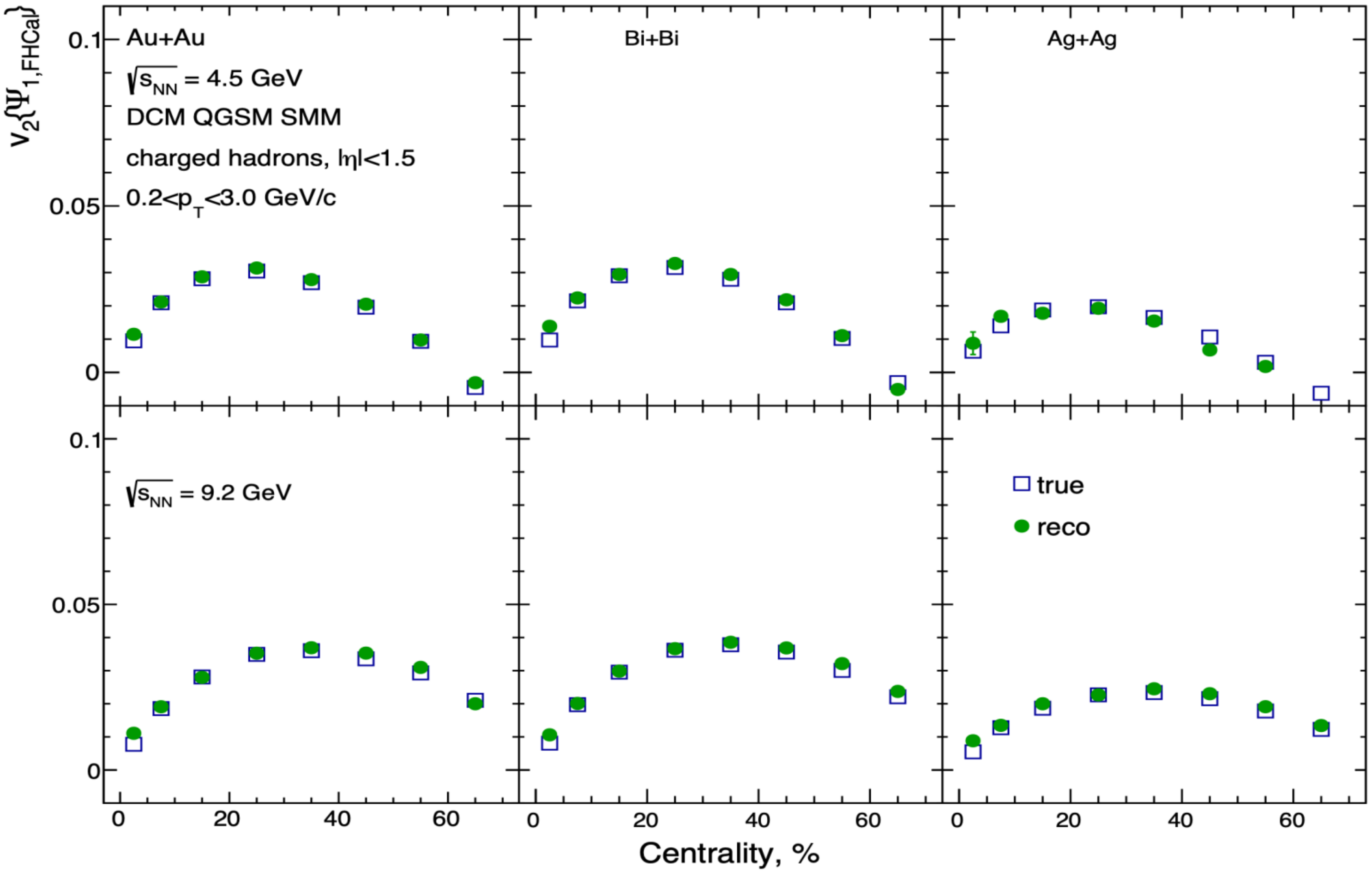


Models show that higher harmonic ripples are more sensitive to the existence of a QGP phase

In models, v_3 goes away when the QGP phase disappears?

15 M of reconstructed vHLLE + UrQMD events for Au+Au at 11.5 GeV

$v_2\{\Psi_{1,\mathrm{FHCal}}\}$



v_n of V0 particles: invariant mass fit method

Data set:

- 25 million events, UrQMD 3.4 non-hydro, 11.0 GeV, minbias

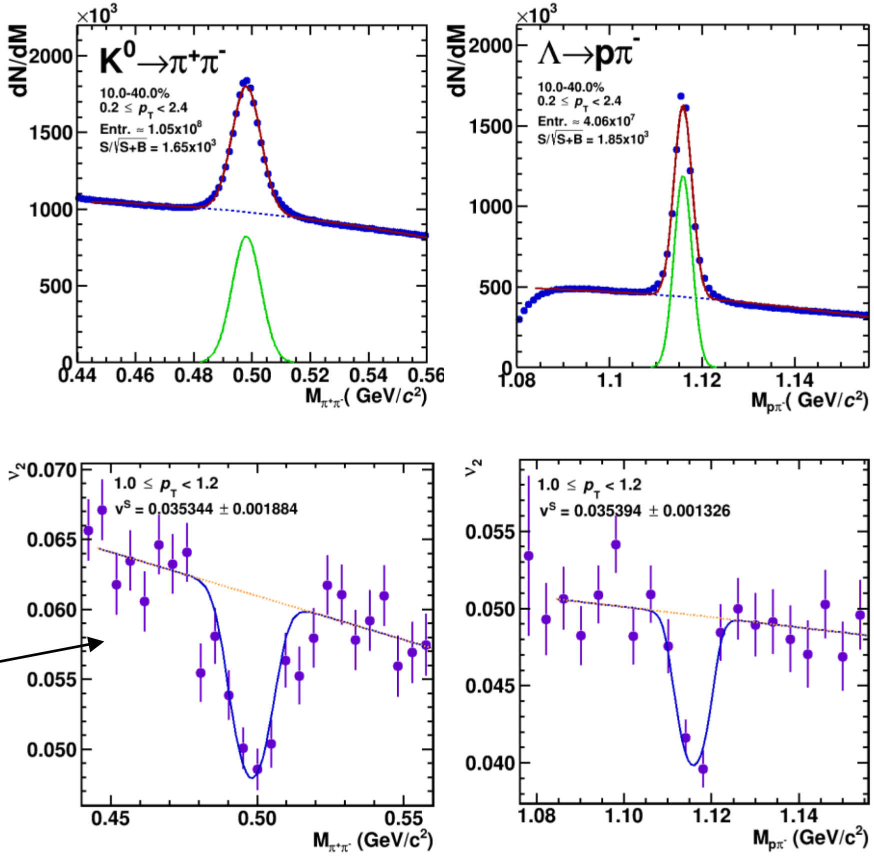
Geant4 simulation, full reconstruction with:

- TPCv7, TOFv7, FHCal

Centrality by TPC multiplicity, Event-plane method with FHCal

Particle decays reconstructed with MpdParticle realistic cuts
Differential flow signal extraction by bins in transverse momentum (or rapidity) with a simultaneous fit

$$v_2^{SB}(m_{inv},p_T) = v_2^S(p_T)\frac{N^S(m_{inv},p_T)}{N^{SB}(m_{inv},p_T)} + v_2^B(m_{inv},p_T)\frac{N^B(m_{inv},p_T)}{N^{SB}(m_{inv},p_T)}$$

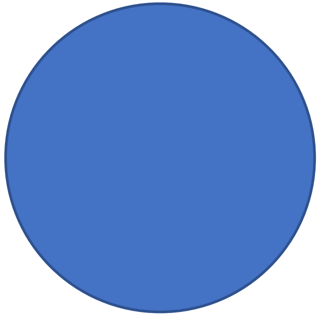


Outlook:
* Larger statistics with vHLLE (hydrodynamic evolution)
* Larger signal magnitude due to hydro (realistic input)
* Latest versions of detector geometry

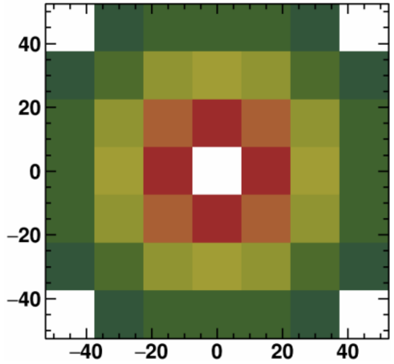
- Multi-variate analysis for reconstructed particle selection (TMVA)
- KFParticle

Non-uniform acceptance corrections

TPC

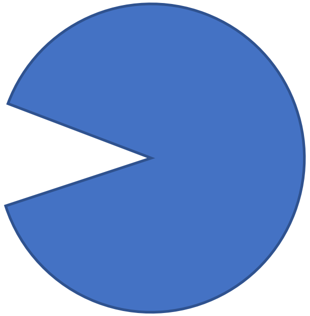


FHCal



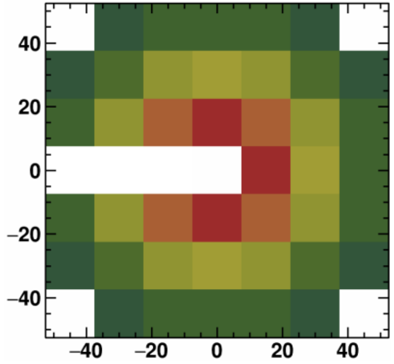
Acceptance filter

TPC



$-165° < \varphi < 165°$

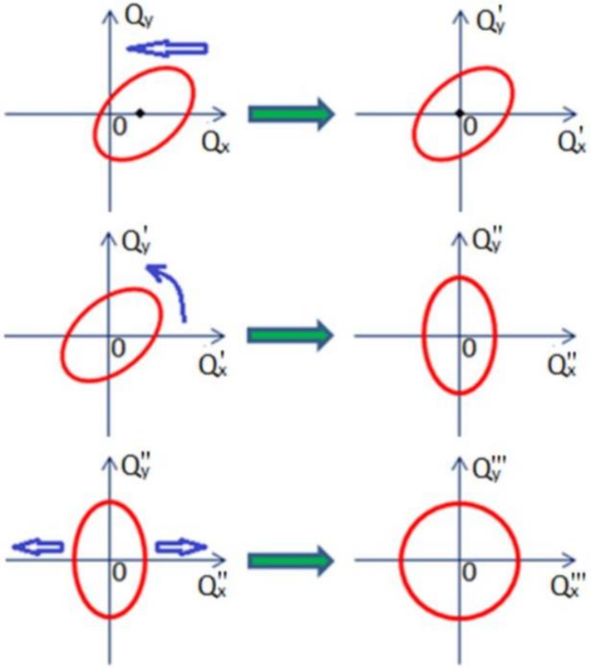
FHCal



Modules 23, 24, 25 (L) and 19, 20, 21 (R) are off

Correction for non-uniform azimuthal acceptance

1. Recentering
2. Twist
3. Rescaling



Corrections are based on method in:
I. Selyuzhenkov and S. Voloshin PRC77, 034904 (2008)

The QnAnalysis package

Motivation:

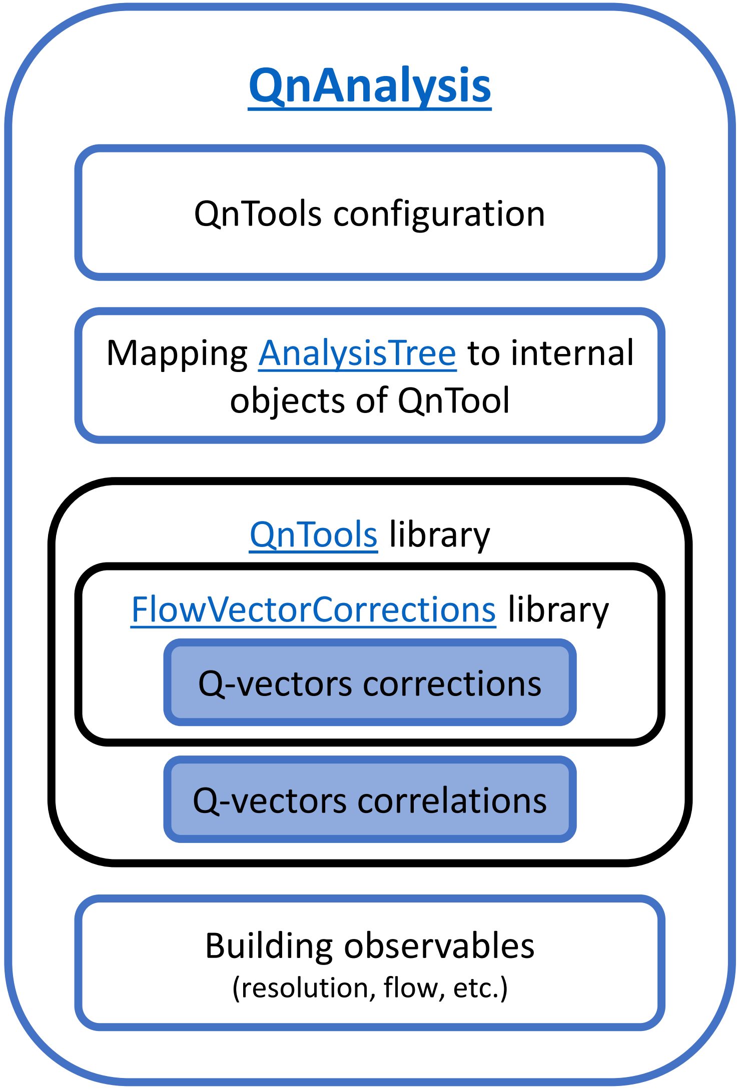
- Decoupling configuration from implementation
- Persistency of analysis setup
- Co-existence of different setups (easy systematics study)
- Unification of analysis methods
- Self-descriptiveness of the analysis results

QnAnalysis requirements:

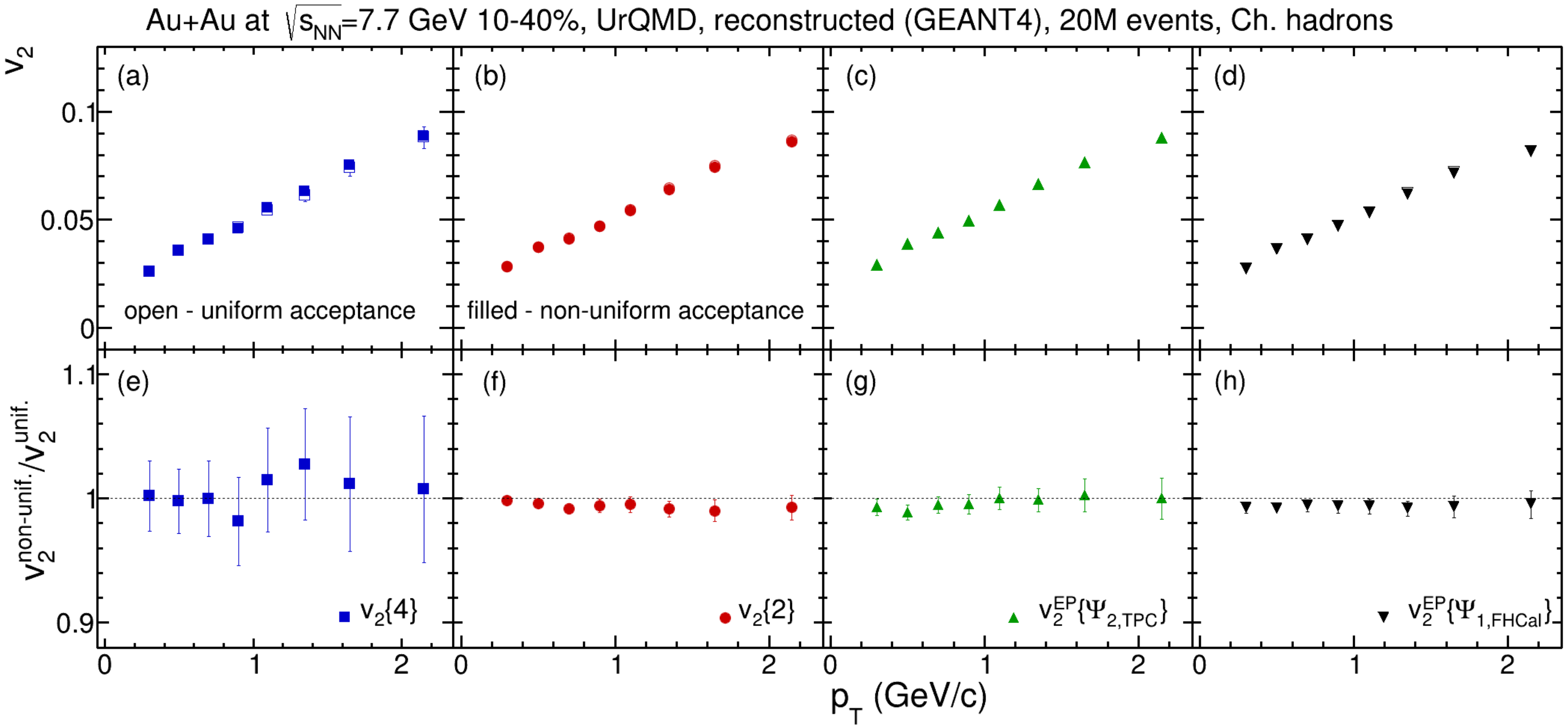
- ROOT ver. ≧ 6.20 (with MathMore library)
- C++17 compatible compiler
- CMake ver. ≧ 3.13

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

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

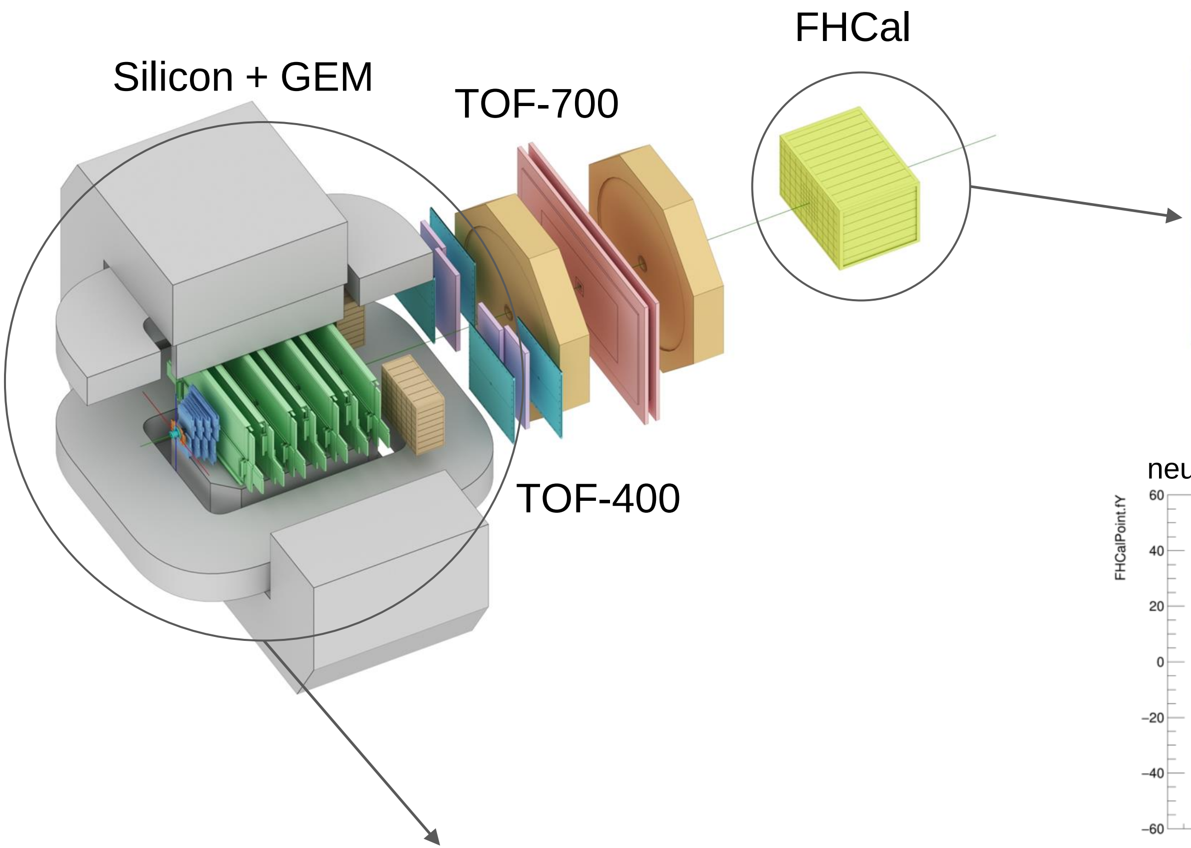


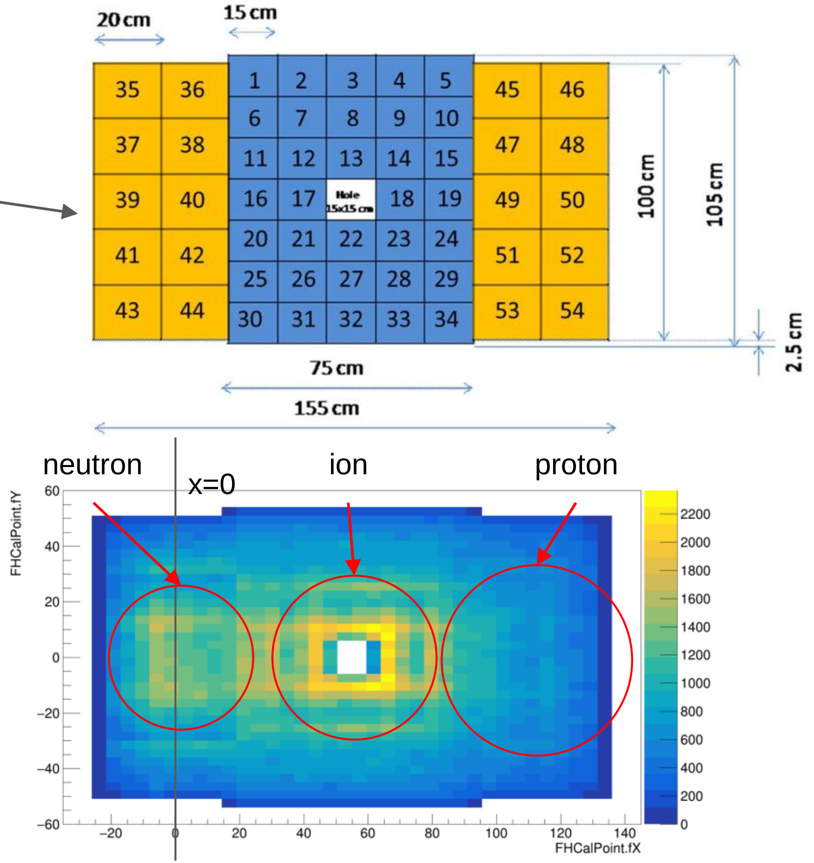
Acceptance correction



The applied acceptance corrections eliminated the influence of non-uniform acceptance

The BM@N experiment (GEANT4 simulation for Xe+Cs(I) run)



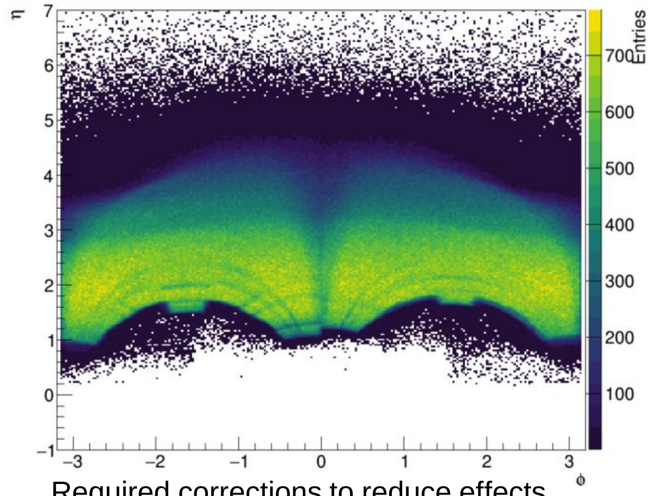


L1 tracking was used together with true-MC PID

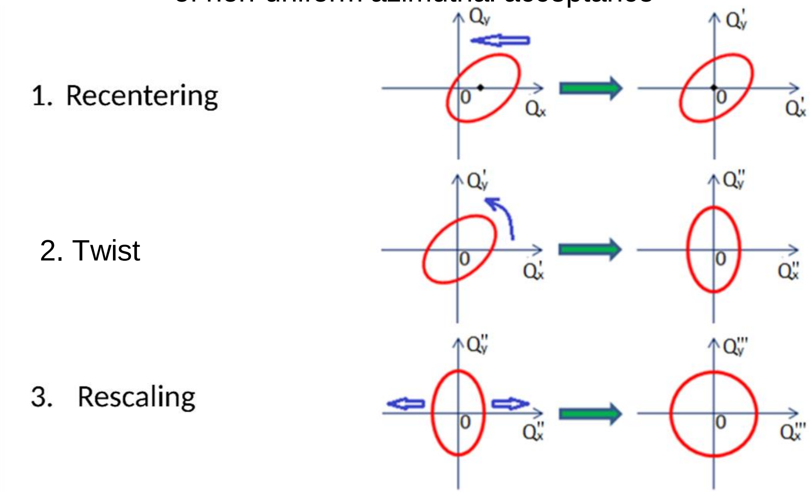
Symmetry plane estimation with the azimuthal asymmetry of projectile spector energy

Azimuthal asymmetry of the BM@N acceptance

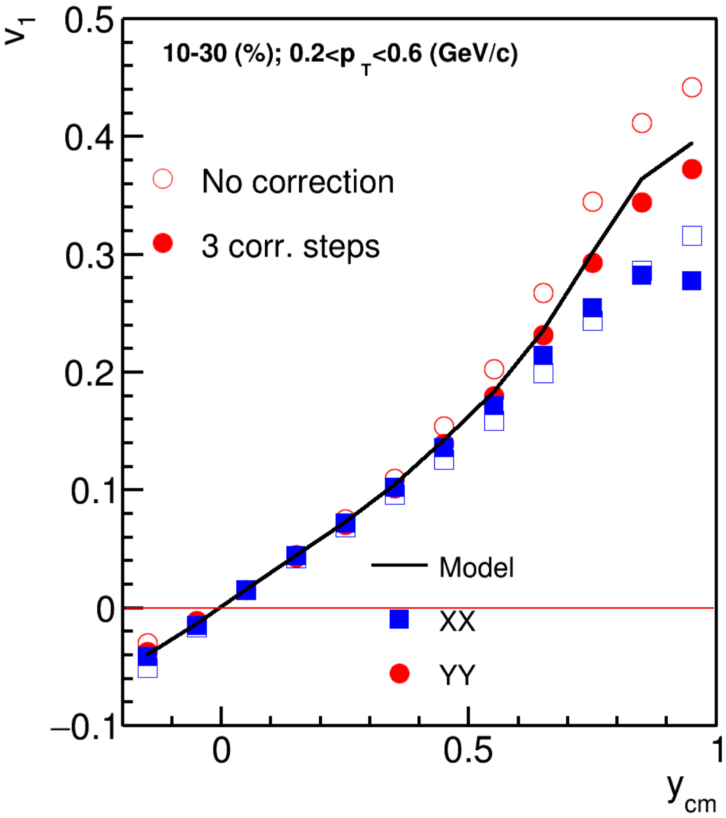
φ-η yield of protons



Required corrections to reduce effects of non-uniform azimuthal acceptance

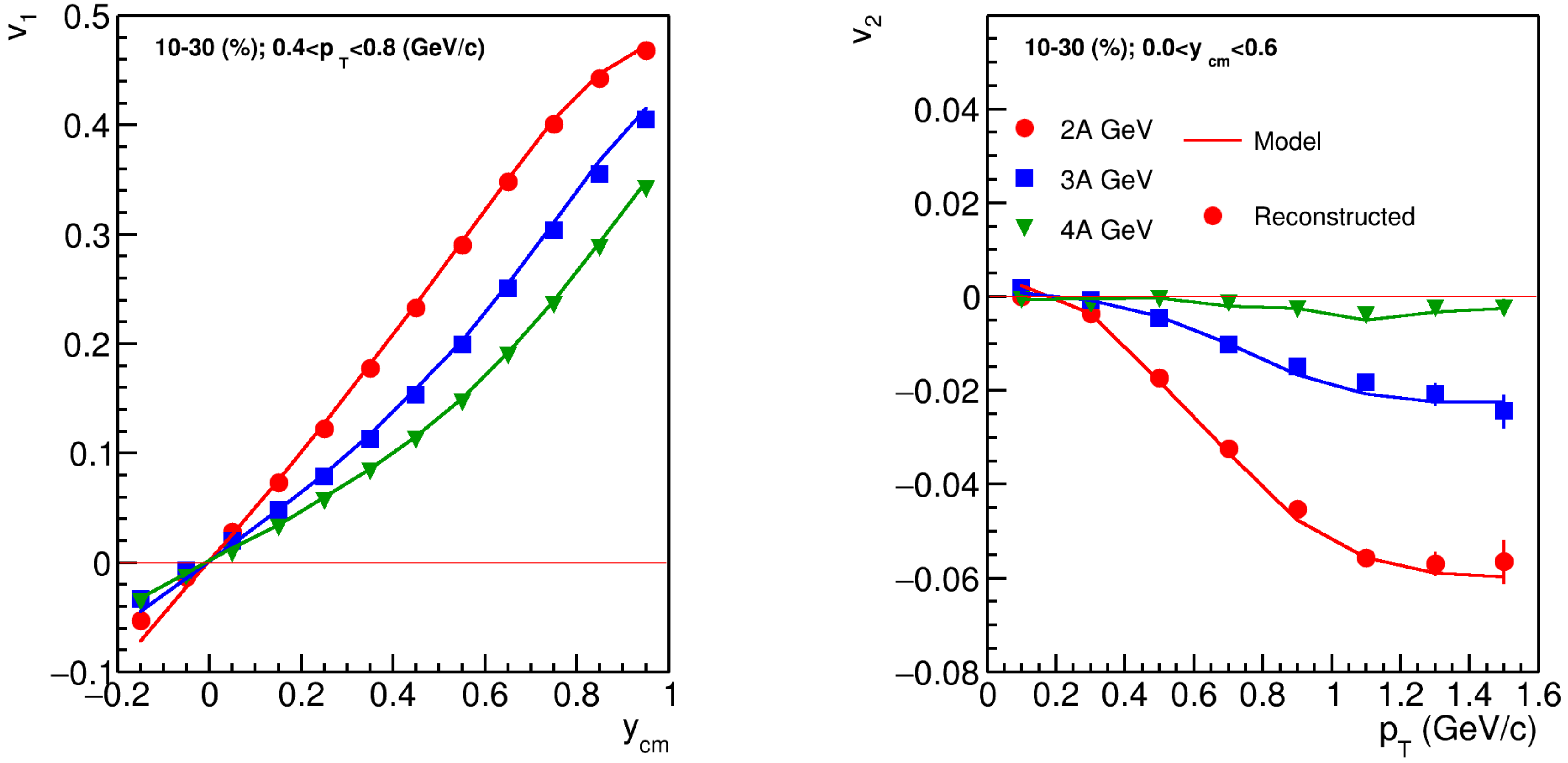


Corrections are based on method in:
I. Selyuzhenkov and S. Voloshin PRC77, 034904 (2008)



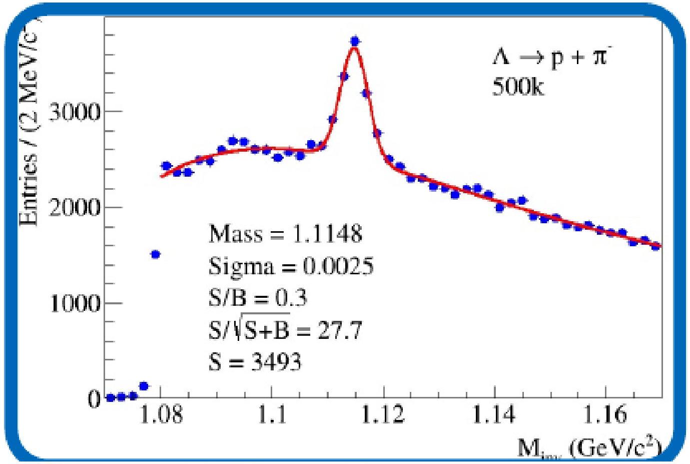
- Better agreement after rescaling for YY
- XX component has a large bias (due to magnetic field)

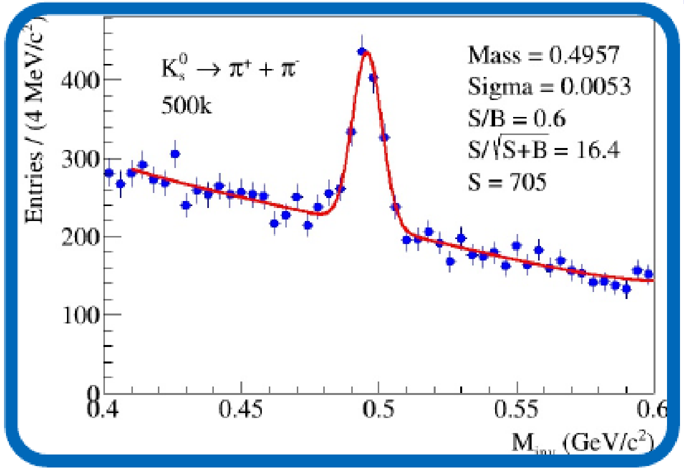
Directed and elliptic flow of protons in Xe+Cs(I) (JAM model)

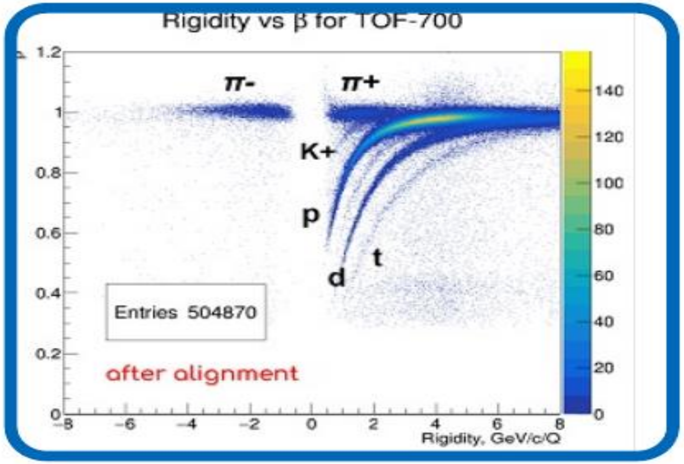


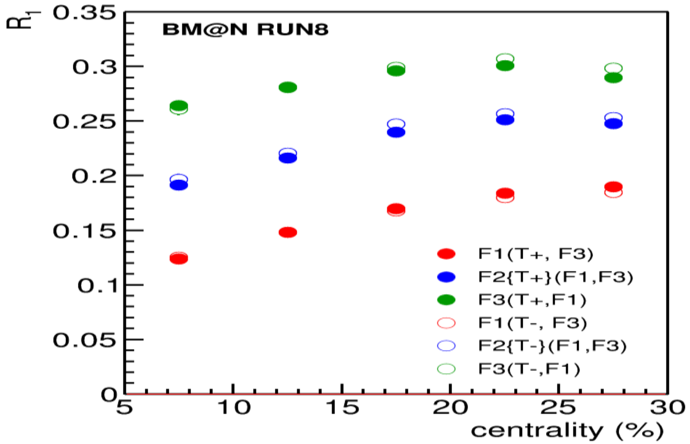
- Good agreement between reconstructed and pure model data for all three energies

BM@N (Baryonic Matter @ Nuclotron)



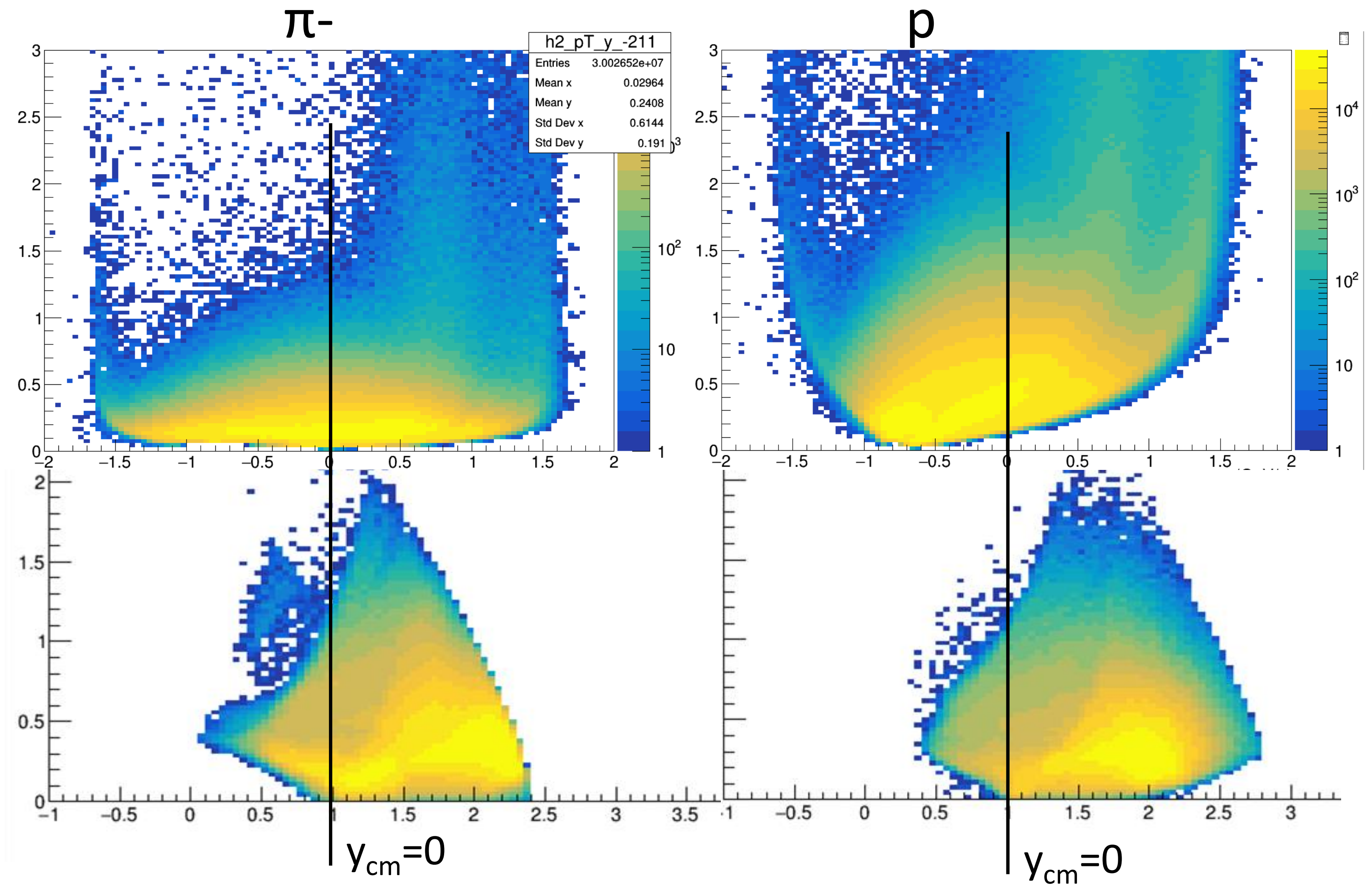






December 2022 – February 2023: first physics run with Xe+Cs(I) (3.0 AGeV (50 M events) и 3.4 AGeV (500 M events))

BM@N vs MPD FXT: p_T-y acceptance

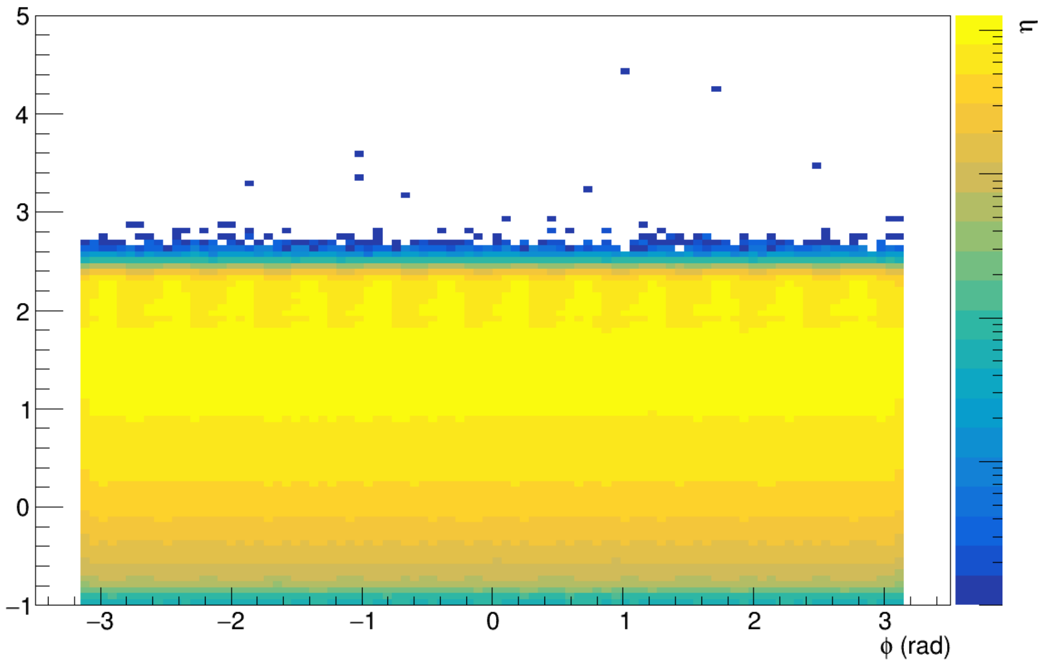


MPD has greater coverage of backward area (even covers projectile spectators) and MPD covers midrapidity region

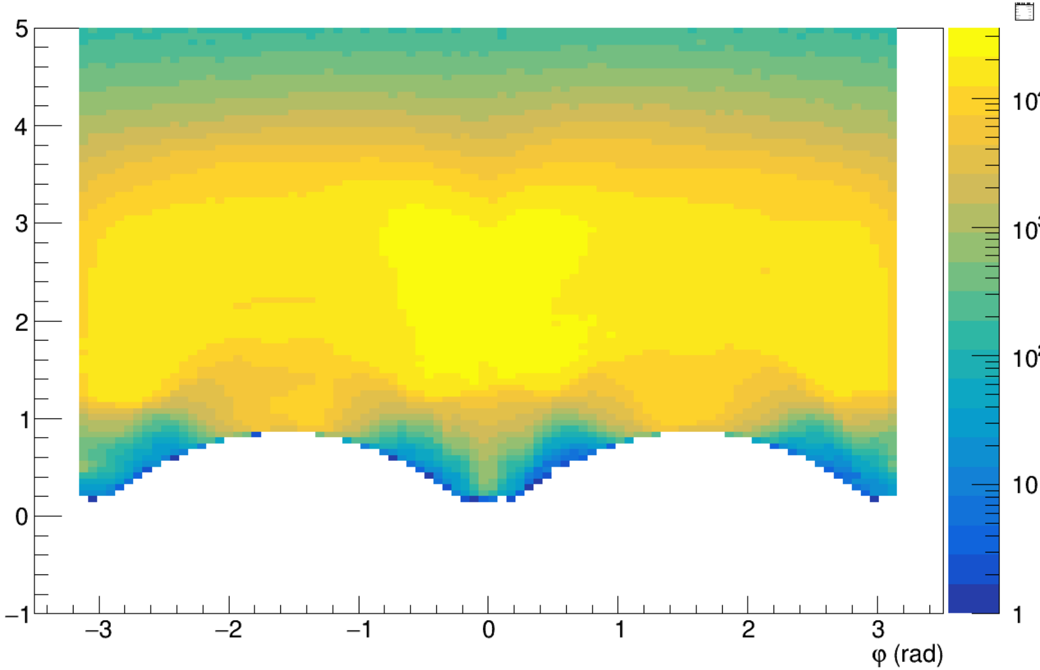
BM@N has greater coverage of forward area

BM@N vs MPD FXT: η-φ acceptance

MPD

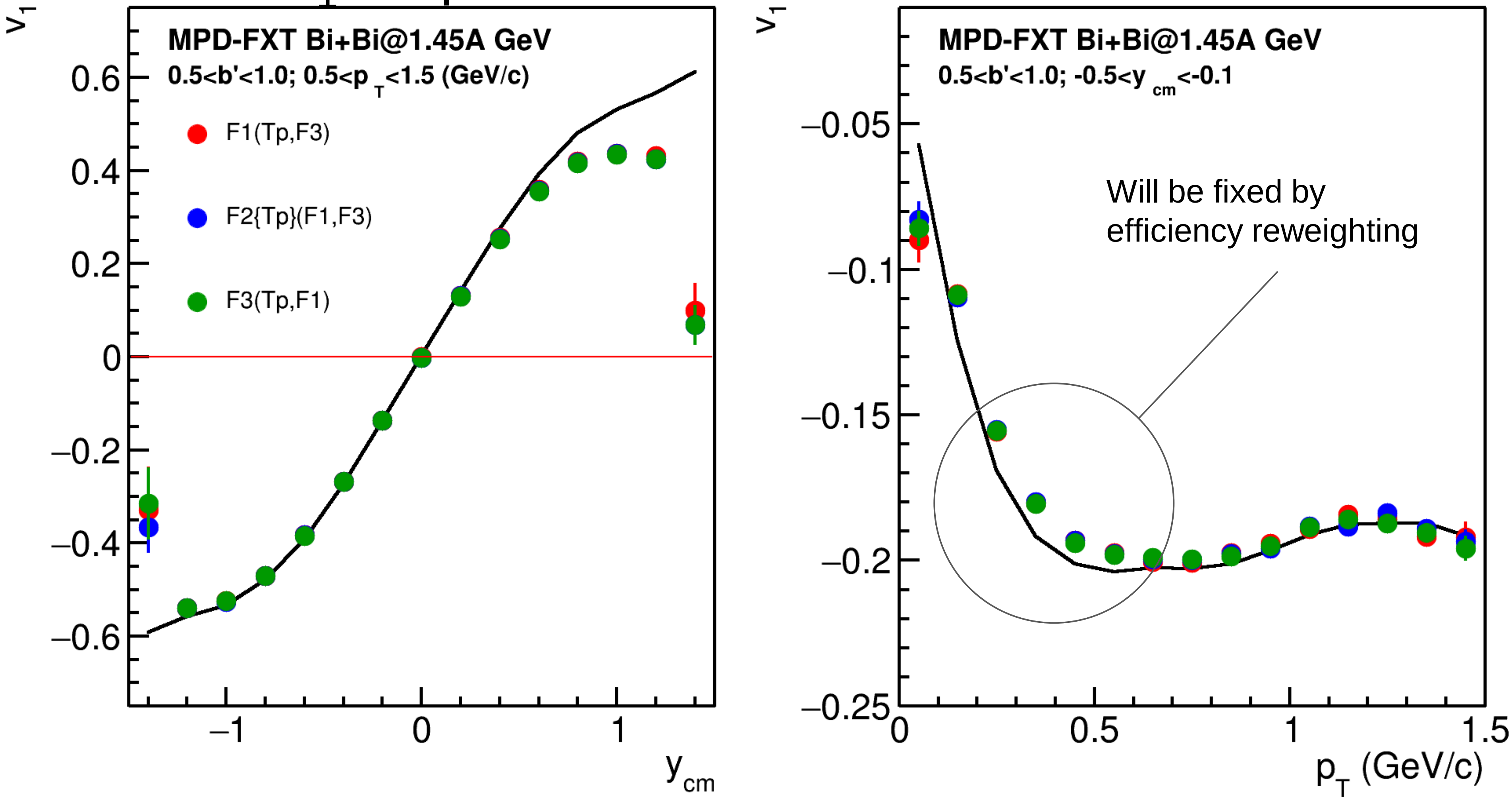


BM@N



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

MPD-FXT: v_1 for protons



v_1 is consistent with model signal for $y < 0.5$

Summary and outlook

- Measurements of anisotropic flow, flow fluctuations, correlations
- between flow of different harmonics are sensitive to many details of the initial conditions
- and the system evolution. It may provides access to the transport properties of the medium: EOS, sound speed (cs), viscosity, etc.
- **v_n at NICA energies shows strong energy dependence:**
  - At $\sqrt{s_{NN}}$=4.5 GeV v_2 from UrQMD, SMASH are in a good agreement with the experimental data
  - At $\sqrt{s_{NN}}\geq$7.7 GeV UrQMD, SMASH underestimate v_2 – need hybrid models with QGP phase
  - Detailed JAM model calculations for differential measurements of v_n at $\sqrt{s_{NN}}$ = 2.4-4.5 GeV
  - v_2 from cumulants of different orders
- **Comparison of methods for elliptic flow measurements using UrQMD and AMPT models:**
  - The differences between methods are well understood and could be attributed to non-flow and fluctuations
- **Feasibility study for anisotropic flow in MPD/MPD FXT/BM@N:**
  - v_n of identified charged hadrons: results from reconstructed and generated data are in a good agreement for all methods
- Programs for flow analysis are available for MPD collaboration:

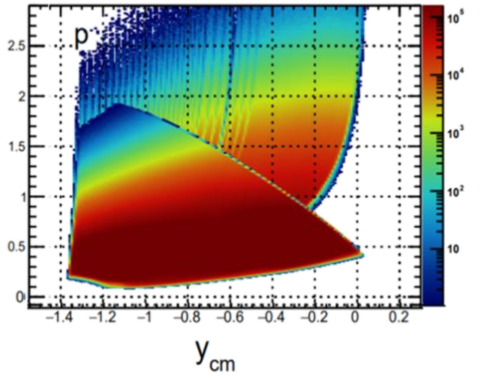
Back-up slides

RHIC BES programs

❖ Data taking by STAR at RHIC: $3 < \sqrt{s_{NN}} < 200$ GeV ($750 < \mu_B < 25$ MeV)

Au+Au Collisions at RHIC											
Collider Runs						Fixed-Target Runs					
	$\sqrt{s_{NN}}$ (GeV)	#Events	μ_B	y_{beam}	run		$\sqrt{s_{NN}}$ (GeV)	#Events	μ_B	y_{beam}	run
1	200	380 M	25 MeV	5.3	Run-10, 19	1	13.7 (100)	50 M	280 MeV	-2.69	Run-21
2	62.4	46 M	75 MeV		Run-10	2	11.5 (70)	50 M	320 MeV	-2.51	Run-21
3	54.4	1200 M	85 MeV		Run-17	3	9.2 (44.5)	50 M	370 MeV	-2.28	Run-21
4	39	86 M	112 MeV		Run-10	4	7.7 (31.2)	260 M	420 MeV	-2.1	Run-18, 19, 20
5	27	585 M	156 MeV	3.36	Run-11, 18	5	7.2 (26.5)	470 M	440 MeV	-2.02	Run-18, 20
6	19.6	595 M	206 MeV	3.1	Run-11, 19	6	6.2 (19.5)	120 M	490 MeV	1.87	Run-20
7	17.3	256 M	230 MeV		Run-21	7	5.2 (13.5)	100 M	540 MeV	-1.68	Run-20
8	14.6	340 M	262 MeV		Run-14, 19	8	4.5 (9.8)	110 M	590 MeV	-1.52	Run-20
9	11.5	157 M	316 MeV		Run-10, 20	9	3.9 (7.3)	120 M	633 MeV	-1.37	Run-20
10	9.2	160 M	372 MeV		Run-10, 20	10	3.5 (5.75)	120 M	670 MeV	-1.2	Run-20
11	7.7	104 M	420 MeV		Run-21	11	3.2 (4.59)	200 M	699 MeV	-1.13	Run-19
						12	3.0 (3.85)	2000 M	750 MeV	-1.05	Run-18, 21

Au+Au @ 3.9 GeV



❖ A very impressive and successful program with many collected datasets, already available and expected results

❖ Limitations:

✓ Au+Au collisions only

✓ Among the fixed-target runs, only the 3 GeV data have full mid-rapidity coverage for protons (|y| < 0.5),