Directed and elliptic flow of protons in the heavy ion collisions at 2-4 GeV

Mikhail Mamaev (NRNU MEPhI, INR RAS)

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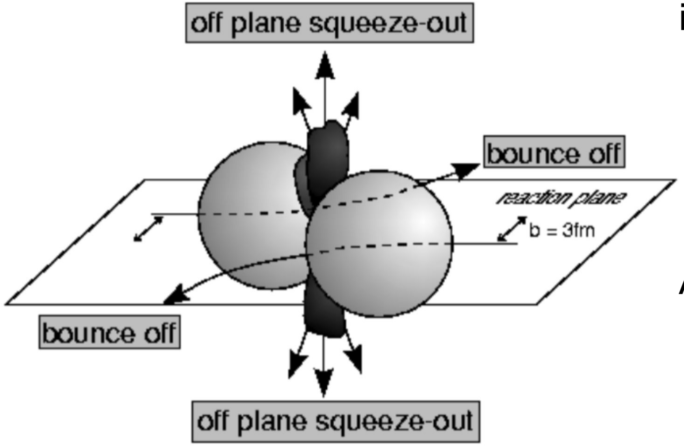
The XXVII International Scientific Conference of Young Scientists and Specialists
30/10/2023

Anisotropic flow & spectators



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

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

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

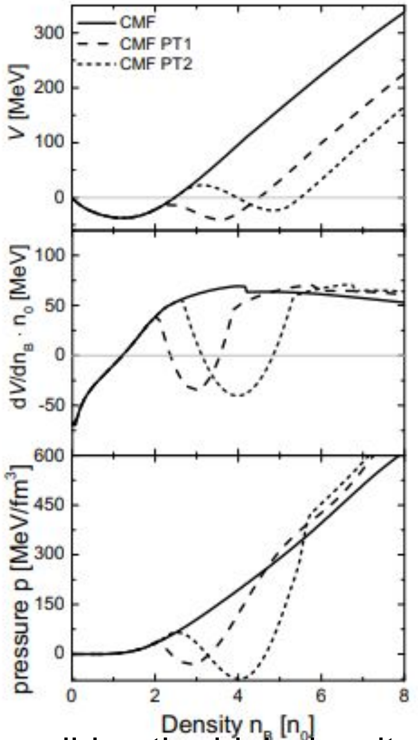
$$t_p = \frac{2R}{\gamma\beta}$$

- Time of the expansion of the created in the collision matter (c_s is speed of sound)

$$t_{exp} = \frac{R}{c_s}$$

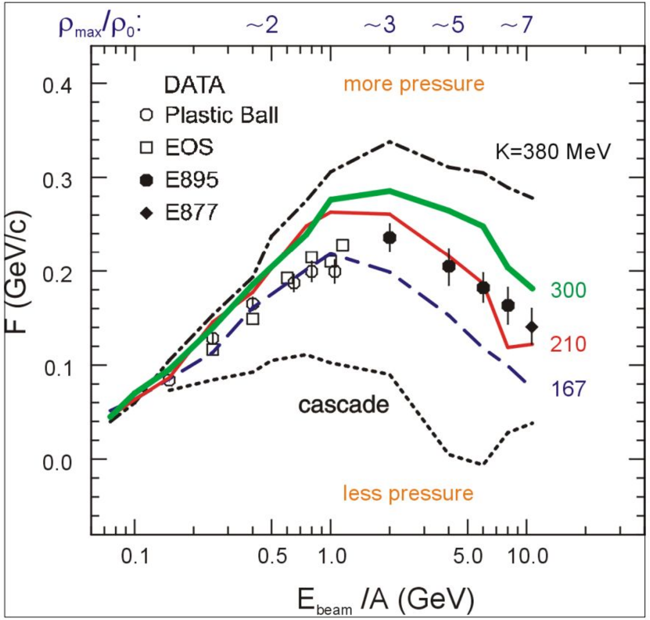
v_n as a function of collision energy

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

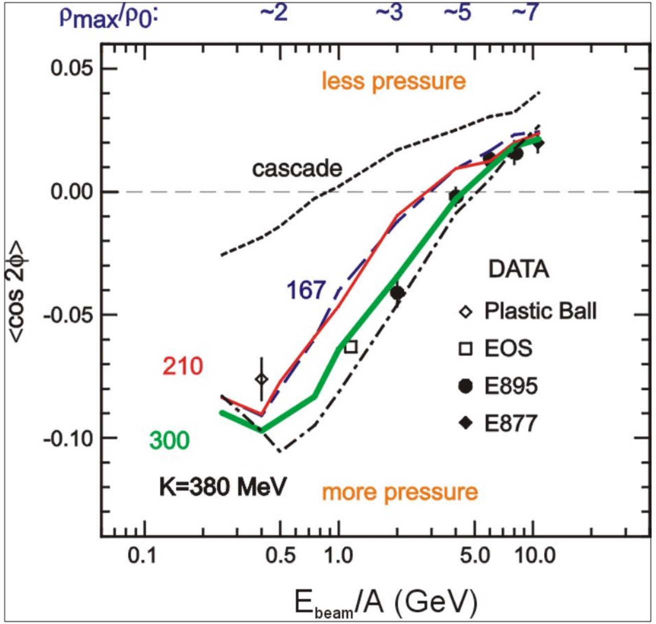


EPJ Web of Conferences 276, 01021 (2023)

v_1 suggests K≈210 MeV



v_2 suggests K=310÷380 MeV



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

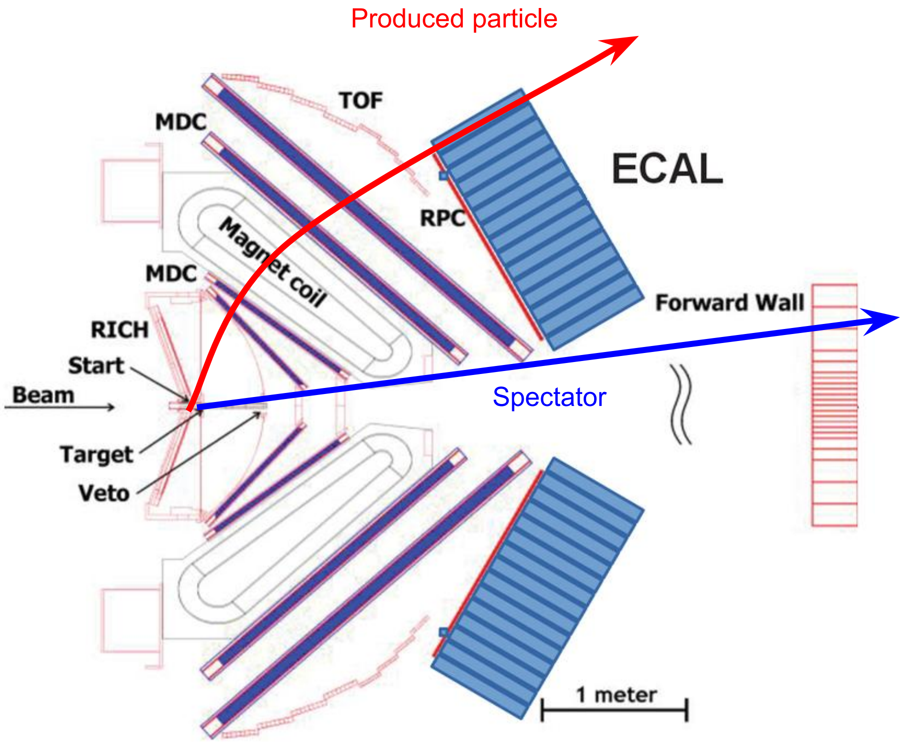
Discrepancy is probably due to non-flow correlations in E895 measurements

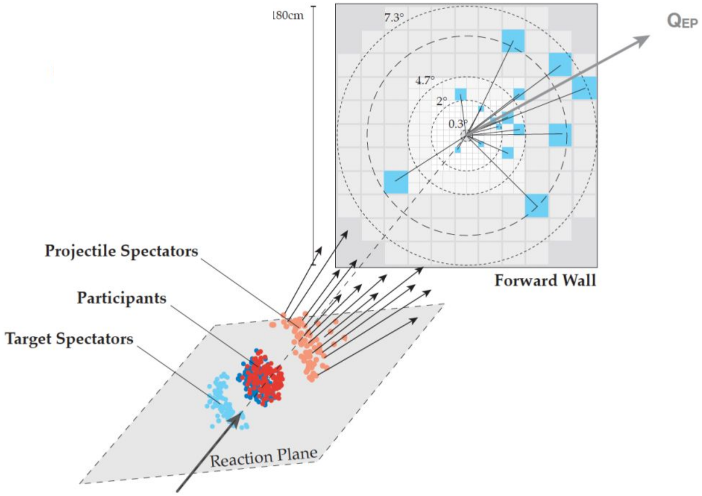
The HADES at SIS-18 accelerator (GSI, Germany)

2012: Au+Au @ E_{lab}=1.23A GeV ($\sqrt{s_{NN}}$=2.4 GeV)

2019: Ag+Ag @ E_{lab}=1.23A GeV ($\sqrt{s_{NN}}$=2.4 GeV)

@ E_{lab}=1.58A GeV ($\sqrt{s_{NN}}$=2.6 GeV)

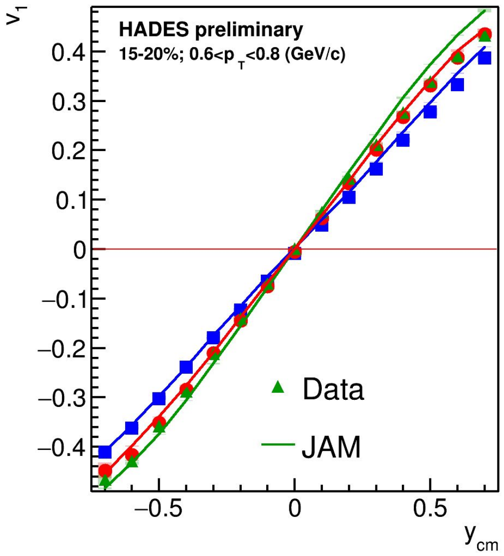


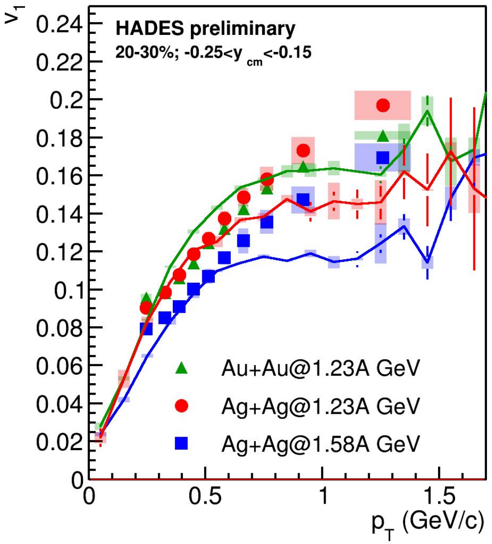


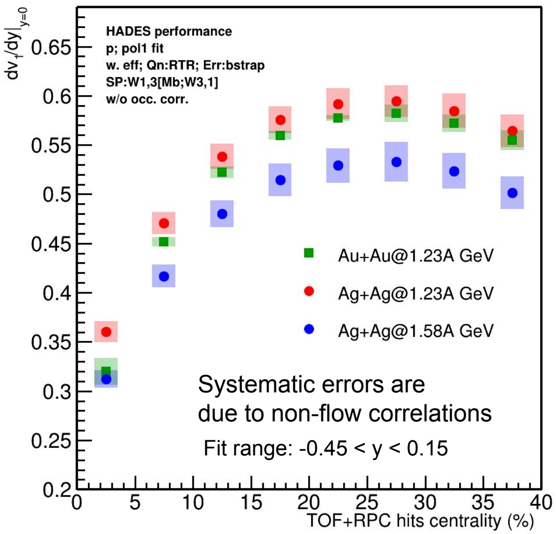
Reaction plane estimation using the deflection of projectile spectors

Proton v_1 vs y, p_T and dv_1/dy vs centrality

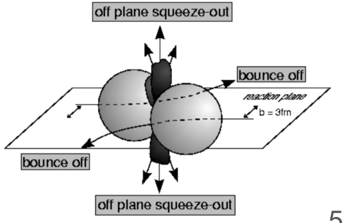
For details of the measurements see [M. Mamaev at FANI-2021 workshop]



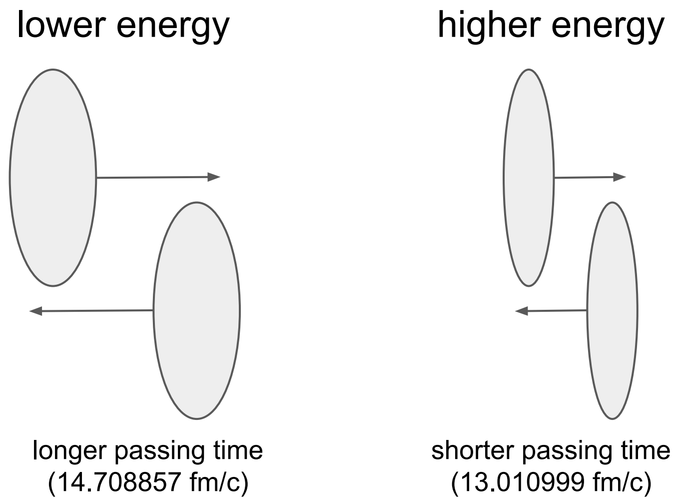




- dv_1/dy is extracted with a fit using a+bx in -0.45 < y < 0.15
- Also tried a general fit form $a+bx+cx^3$ with (a!=0)
  and without intercept (a=0) in different fit ranges (-0.65 < y < 0.15): same result



dv_1/dy scaling with collision energy and system size

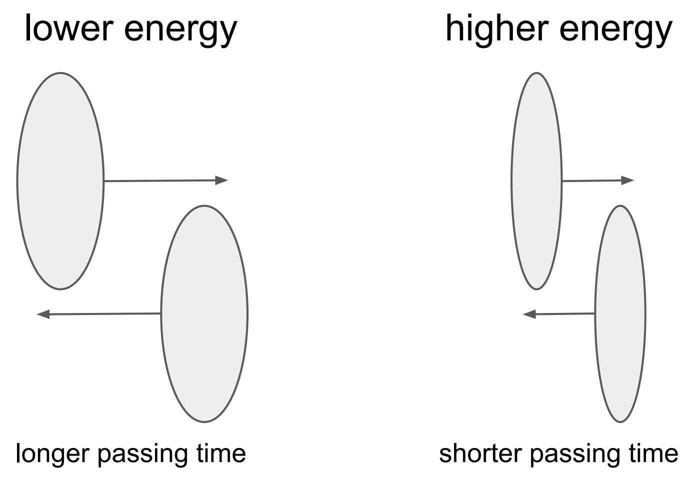


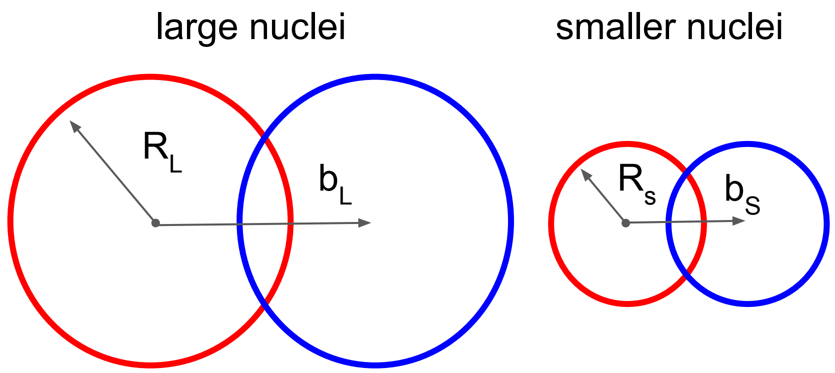
During the passing time of nuclei:

- Protons composing the hot matter in the overlap region are mixed with protons within cold spectator matter
- Expansion of the matter within the overlap region deflects protons in the reaction plane ⇨ positive directed flow of protons

$dv_1/dy|_{y=0}$ is proportional to passing time $t_p=2R/\sinh(y_{beam})$ ⇨ scaling with y_{beam} is expected

dv_1/dy scaling with collision energy and system size





v_1 reflects the initial asymmetry of the overlap region ➪ expect similar v_1 for the same relative impact parameter b/R

$$b_L/R_L = b_s/R_s$$

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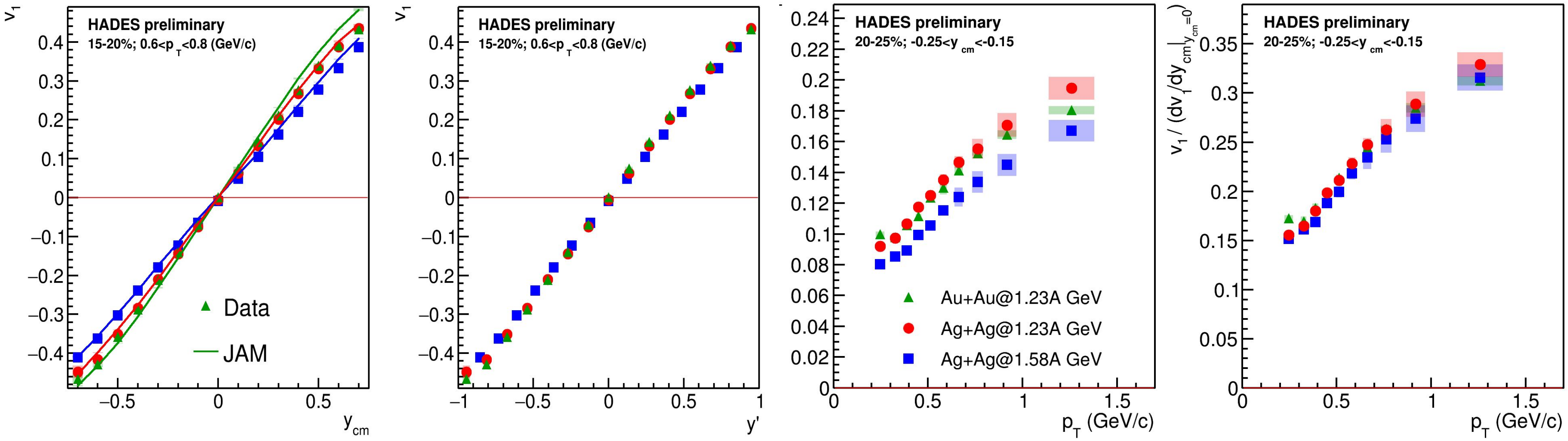
v_1 scaling with collision energy and system size

$t_{Au+Au@1.23A\ GeV}$ = 18 fm/c

$t_{Ag+Ag@1.23A\ GeV}$ = 15 fm/c

$t_{Ag+Ag@1.58A\ GeV}$ = 13 fm/c

$y_{CM} \rightarrow y' = y_{CM} / y_{beam}$ $\qquad$ $v_1 (p_T) \rightarrow v_1(p_T) / dv_1/dy$



- Scaled v_1 does not depend on system size and energy of the collision
- Shape of the v_1 vs p_T does not change with system size and energy of the collision

dv_1/dy scaling with collision energy and system size

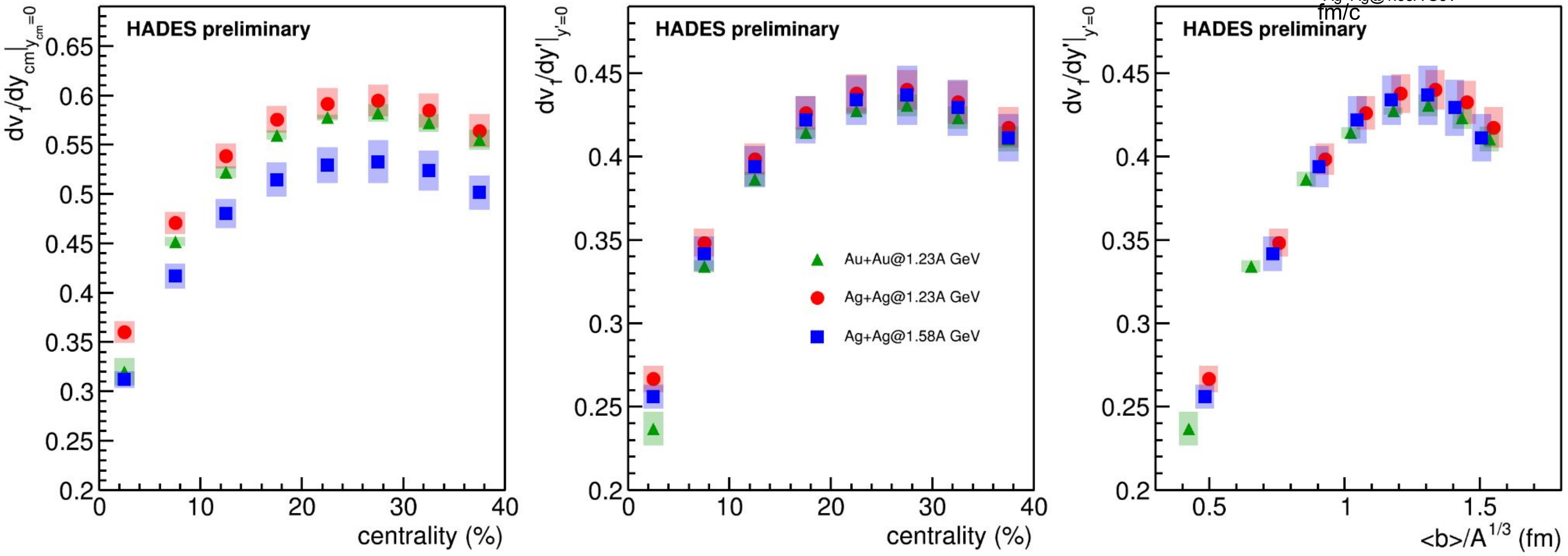
$t_{Au+Au@1.23A\ GeV}$ = 18 fm/c

$t_{Ag+Ag@1.23A\ GeV}$ = 15 fm/c

$t_{Ag+Ag@1.58A\ GeV}$ = 13 fm/c

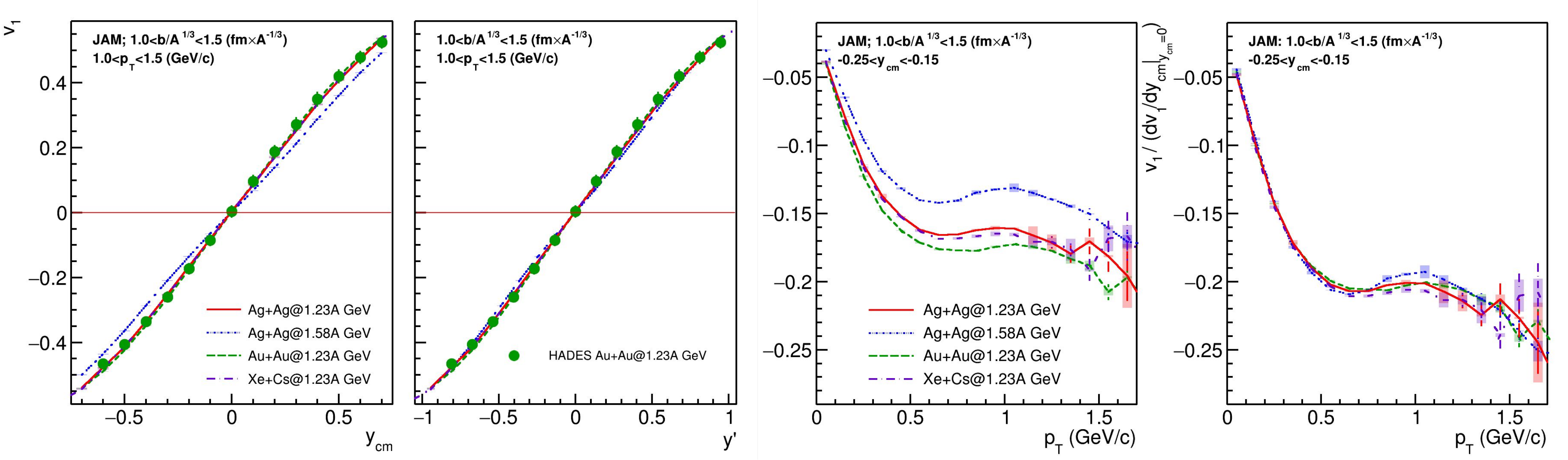
$y_{CM} \rightarrow\ y' = y_{CM} / y_{beam}$

Centrality → <b> / $A^{1/3}$



- After correcting for dependence on the passing time (y_{beam}) dv_1/dy' is independent of the size of colliding nuclei and collision energy and depends only on the relative impact parameter (<b> / $A^{1/3}$)

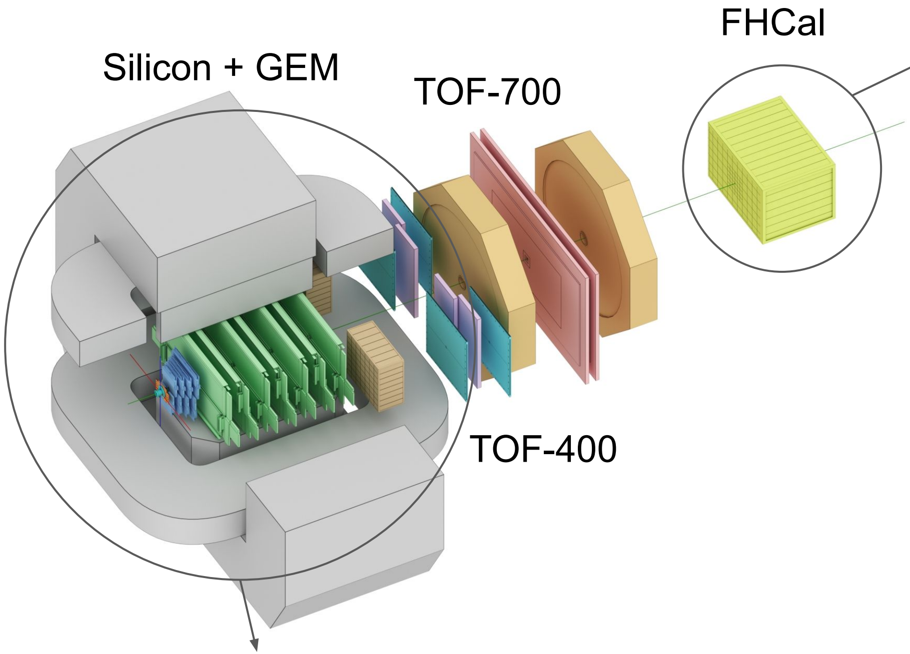
JAM-MF: v_1 scaling with collision energy and system size



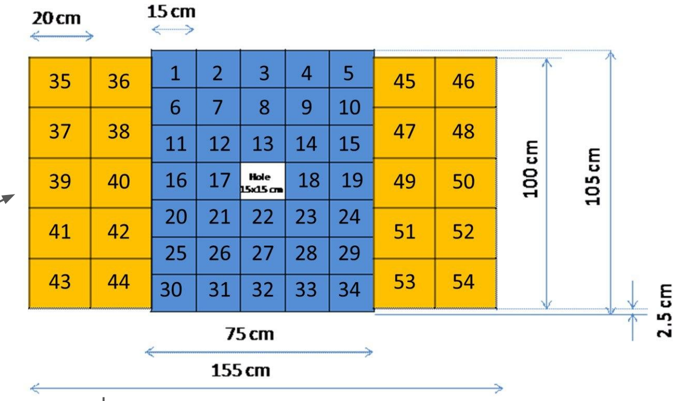
- We observe similar scaling properties in JAM-MF model

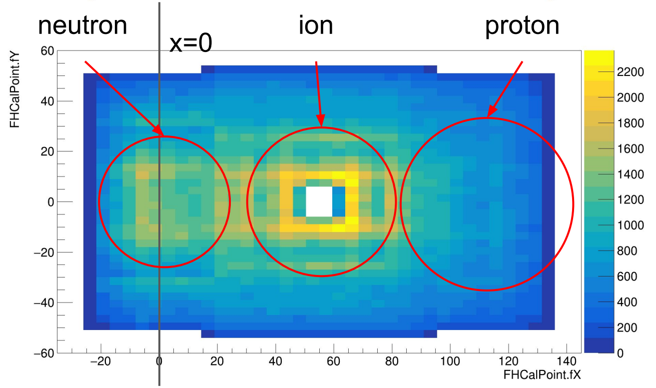
The BM@N experiment

- Xe+CsI at E_{kin}=3.8A GeV
- First physical run



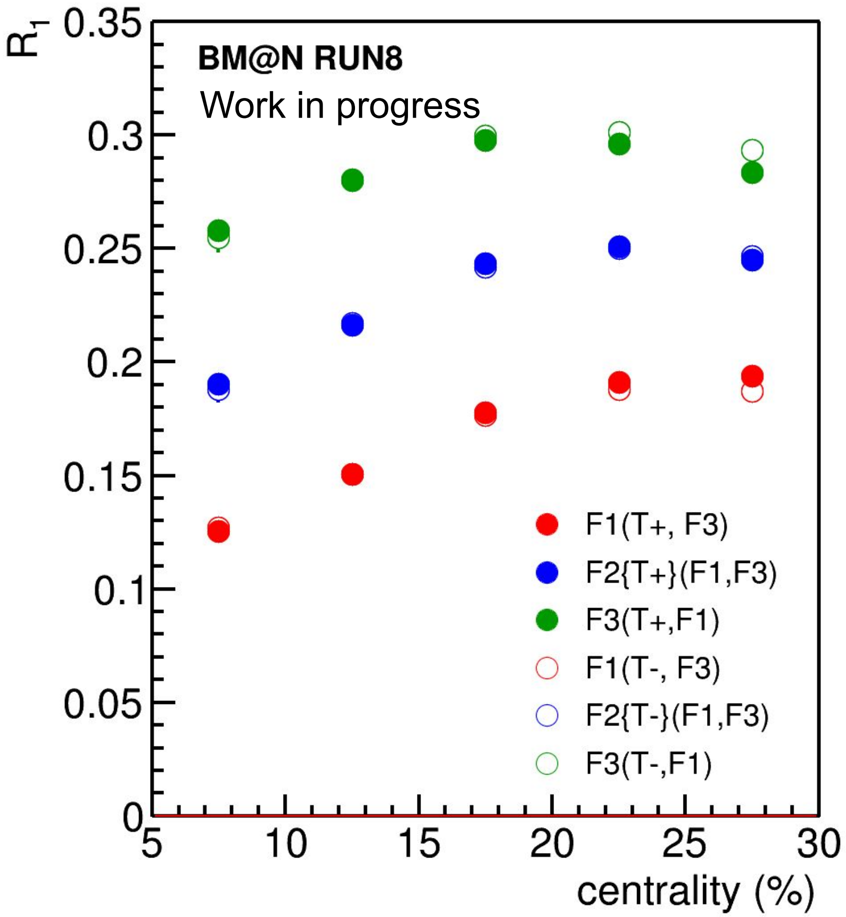
Tracking system within the magnetic field

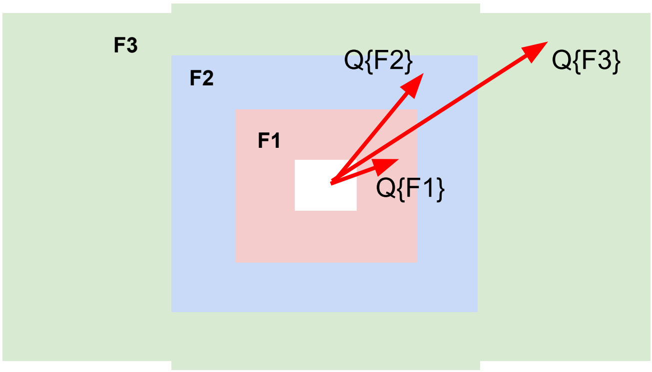




Symmetry plane estimation with the azimuthal asymmetry of projectile spector energy

R1: BM@N Run8 DATA: Xe+Cs@3.8A GeV





T-: all negatively charged particles with:
- $1.5 < \eta < 4$
- $p_T > 0.2$ GeV/c

T+: all positively charged particles with:
- $2.0 < \eta < 3$
- $p_T > 0.2$ GeV/c

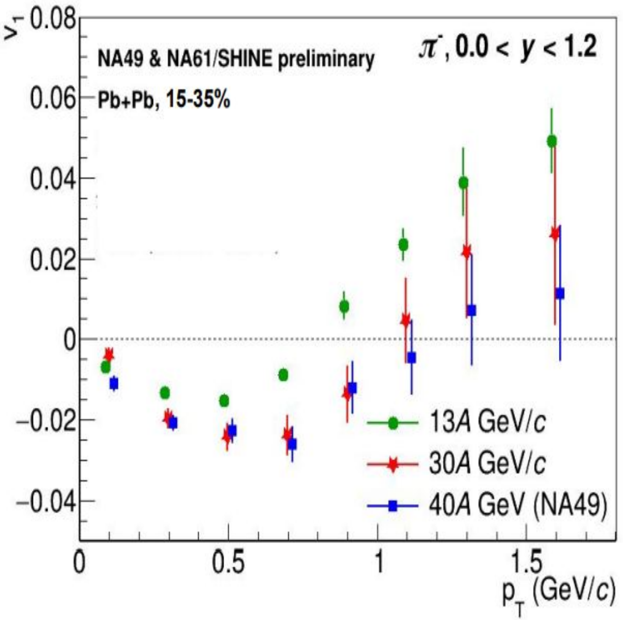
Results for v_1 and v_2 are in progress

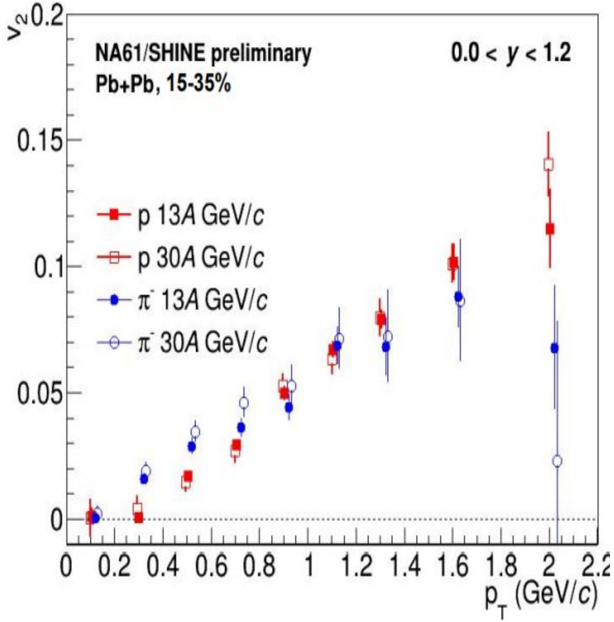
Summary

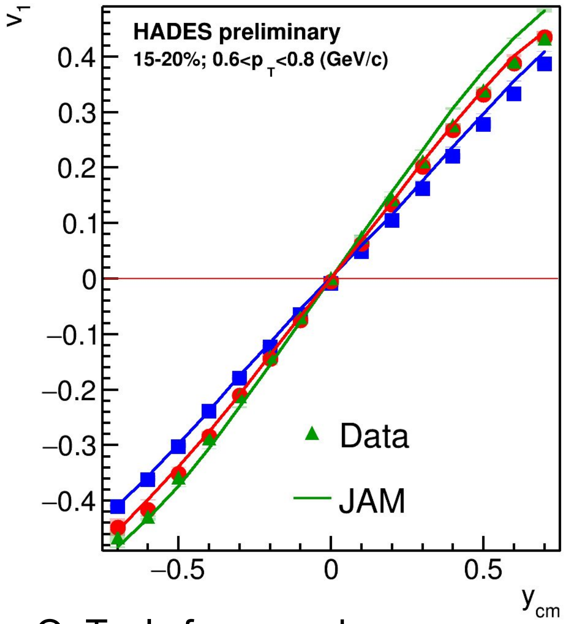
- At $\sqrt{s_{NN}}$=2.4-2.6 GeV (E_{kin}=1.23-1.58) region we observe dv_1/dy scaling with collision energy (passing time / y_{beam}) and system size:
  - dv_1/dy' is independent of the size of colliding nuclei and collision energy
  - dv_1/dy' depends only on the relative impact parameter (<b> / $A^{1/3}$)
  - based on the preliminary results of the HADES experiment we observe v_1 is strongly influenced by the interaction with spectator matter
- The analysis of the recent BM@N experimental run is ongoing:
  - The resolution correction factor R_1 calculated using different combinations of Q-vectors is consistent within the statistical errors

BACKUP

QnTools framework

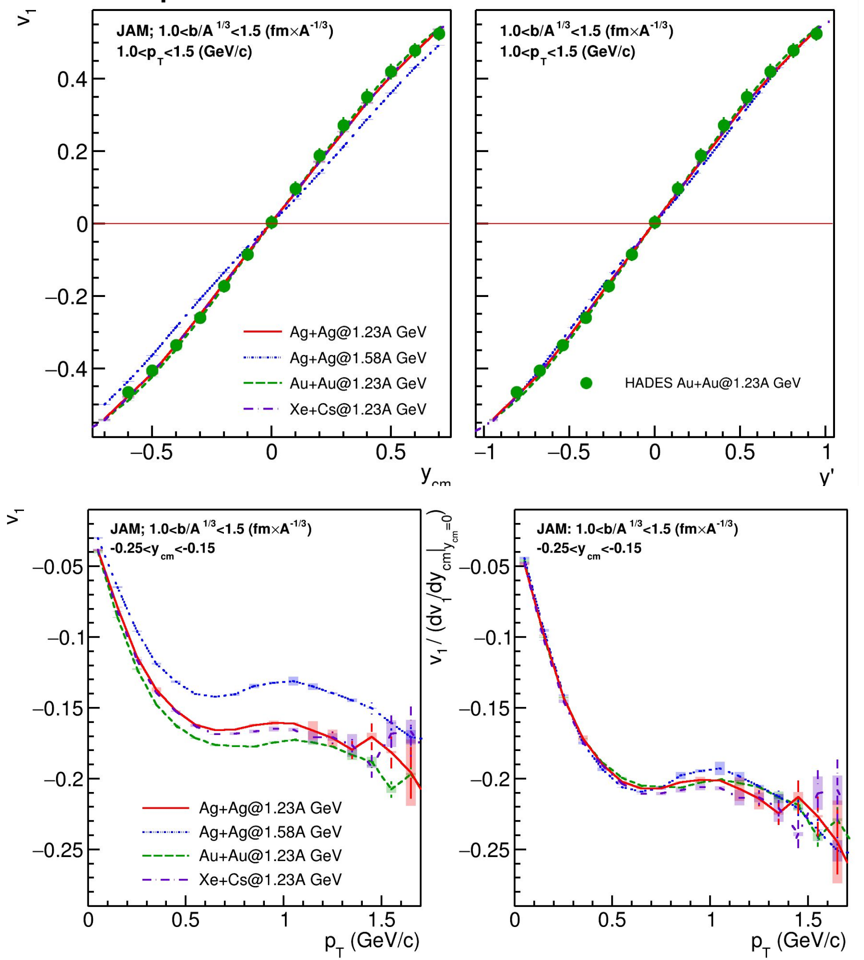






- All the methods used for performance study were carried out using QnTools framework: https://github.com/HeavyIonAnalysis/QnTools (well documented and well-tested)
- Methods for flow measurements in fixed-target experiments were tested on experimental data from NA61/SHINE, HADES and ALICE
- Tested and implemented in MPD root

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

Flow vectors

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

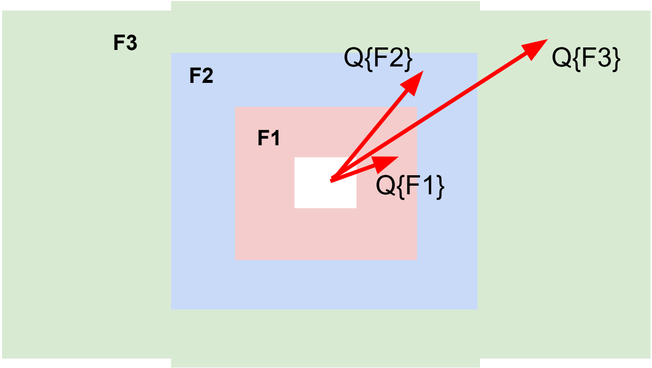
$$u_n = e^{in\phi}$$

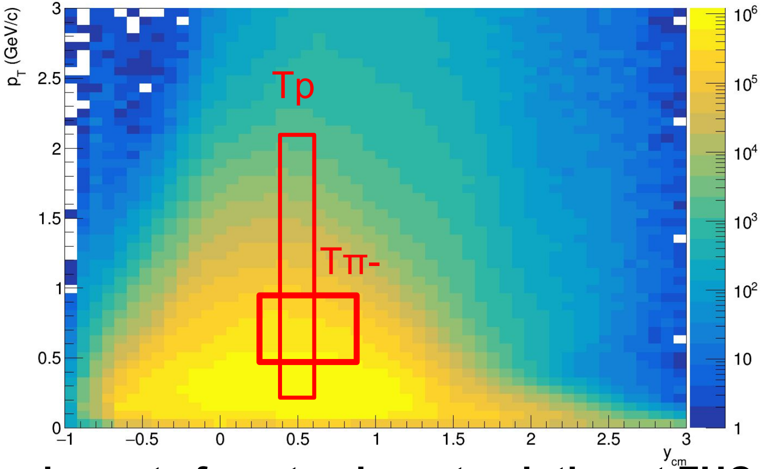
where φ is the azimuthal angle

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





Additional subevents from tracks not pointing at FHCal:

Tp: p; 0.4<y<0.6; 0.2 < p_T < 2 GeV/c; w=1/eff

Tπ: π-; 0.2<y<0.8; 0.1 < p_T < 0.5 GeV/c; w=1/eff

T-: all negative; 1.0<η<2.0; 0.1 < p_T < 0.5 GeV/c; w=1/eff

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

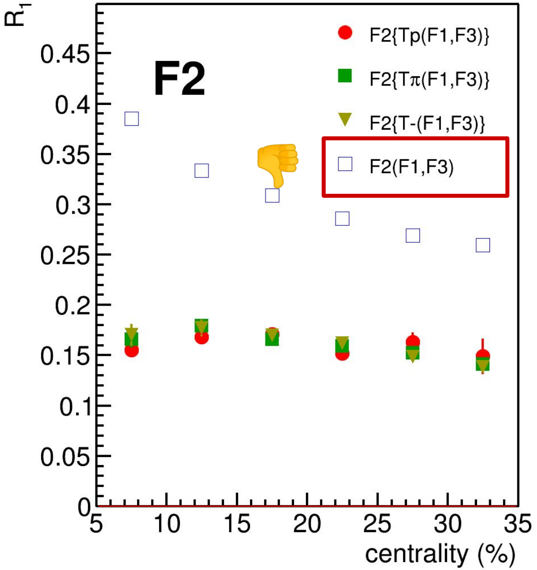
Scalar product (SP) method:

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

Where R_1 is the resolution correction factor

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

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



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

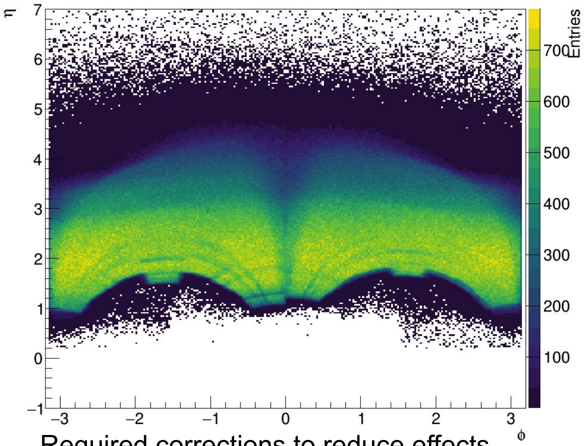
$$R_1^{F2(F1,F3)} = \frac{\sqrt{\langle Q_1^{F2} Q_1^{F1} \rangle \langle Q_1^{F2} Q_1^{F3} \rangle}}{\sqrt{\langle Q_1^{F1} Q_1^{F3} \rangle}}$$

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

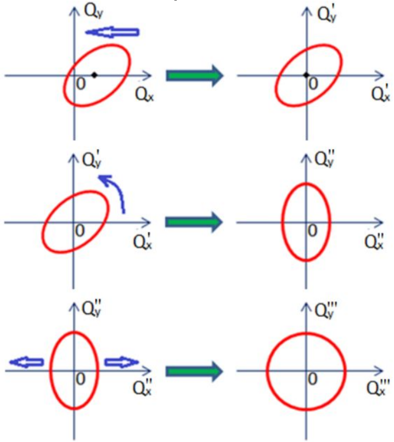
$$R_1^{F2\{Tp\}(F1,F3)} = \langle Q_1^{F2} Q_1^{Tp} \rangle \frac{\sqrt{\langle Q_1^{F1} Q_1^{F3} \rangle}}{\sqrt{\langle Q_1^{Tp} Q_1^{F1} \rangle \langle Q_1^{Tp} Q_1^{F3} \rangle}}$$

Azimuthal asymmetry of the BM@N acceptance

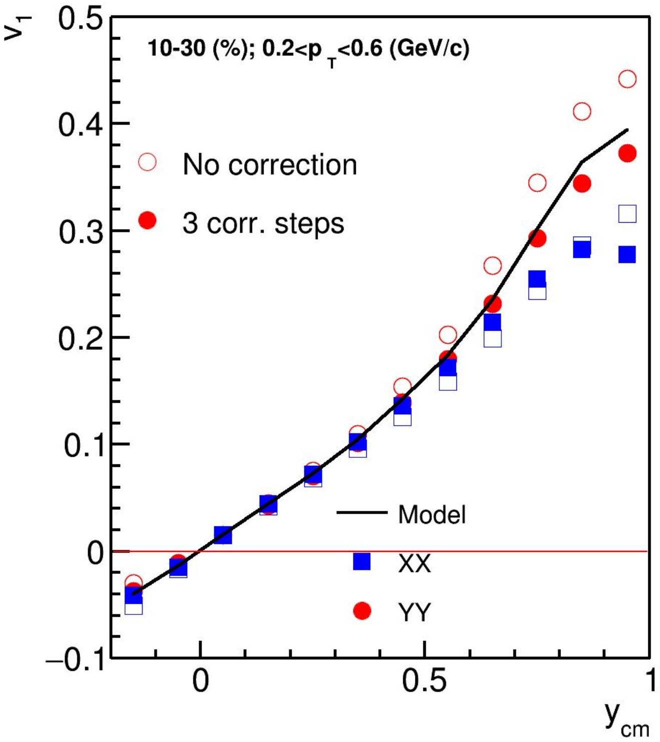
φ-η yield of protons



Required corrections to reduce effects of non-uniform azimuthal acceptance

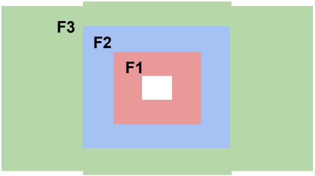


Corrections are based on method in:
I. Selyuzhenkov and S. Voloshin PRC77, 034904 (2008)

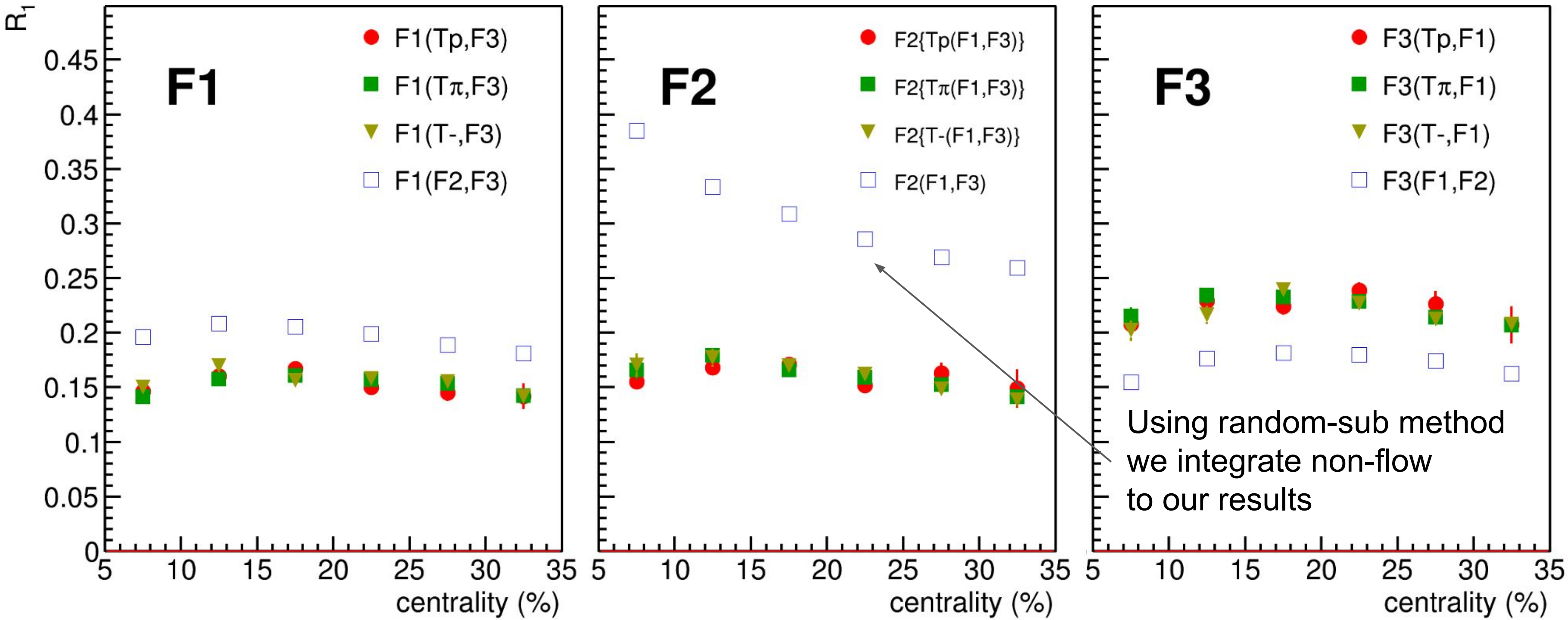


- Better agreement after rescaling for YY
- XX component has a large bias (due to magnetic field)

SP R1: DCMQGCM-SMM Xe+Cs@4A GeV



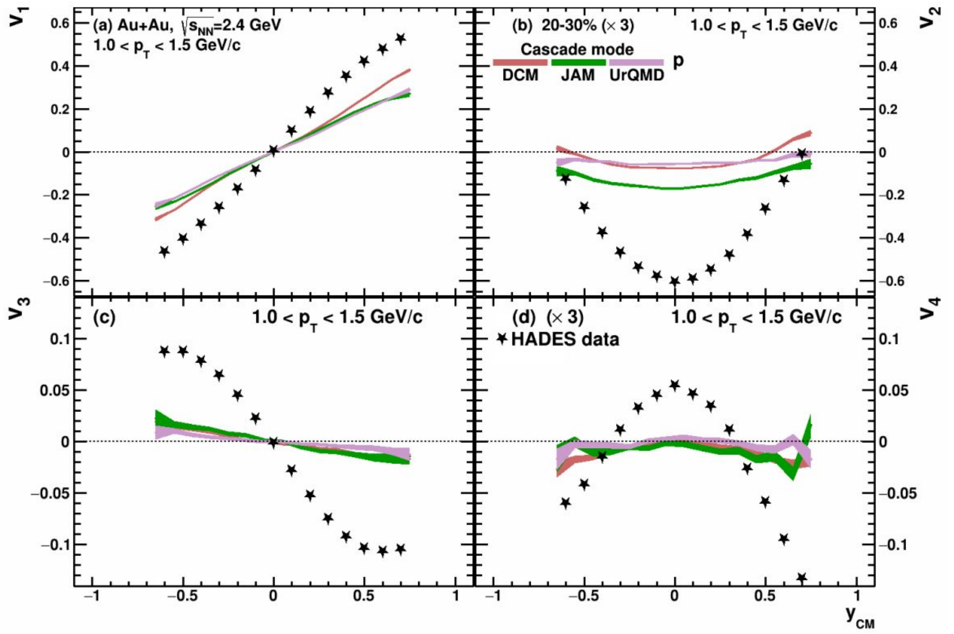
SP gives unbiased estimation of v_n (root-mean-square)
EP gives biased estimation (somewhere between mean and RMS)

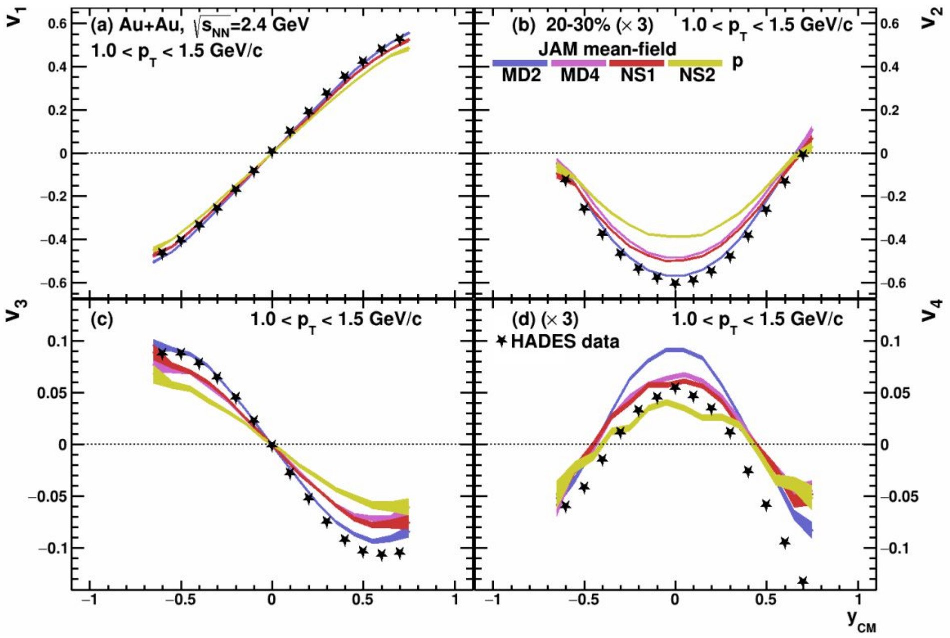


Using the additional sub-events from tracking provides a robust combination to calculate resolution

Models

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





- Cascade mode fail to reproduce flow signal
- Mean-Field models reproduce flow signal up to 4th harmonic

Simulation datasample

- Xe+Cs nuclei collisions
- DCMQGSM-SMM model (realistic yields of spectator fragments), describes flow poorly
- JAM model (realistic flow signal)
- Geant4 transport code (important for simulation of hadronic showers in the forward calorimeter)

- Realistic reconstruction

	2A GeV	3A GeV	4A GeV
DCMQGSM-SMM	6M	6M	2M
JAM MD2	3M	3M	5M

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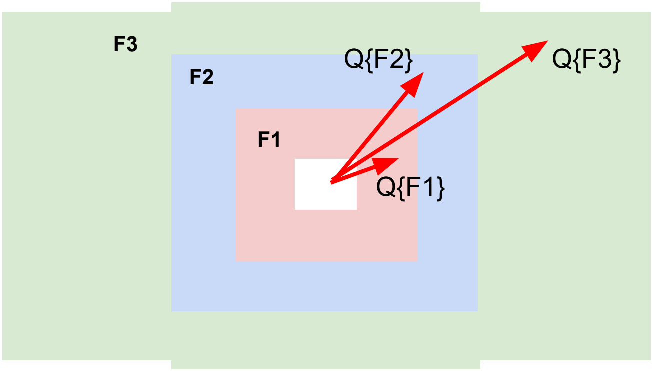

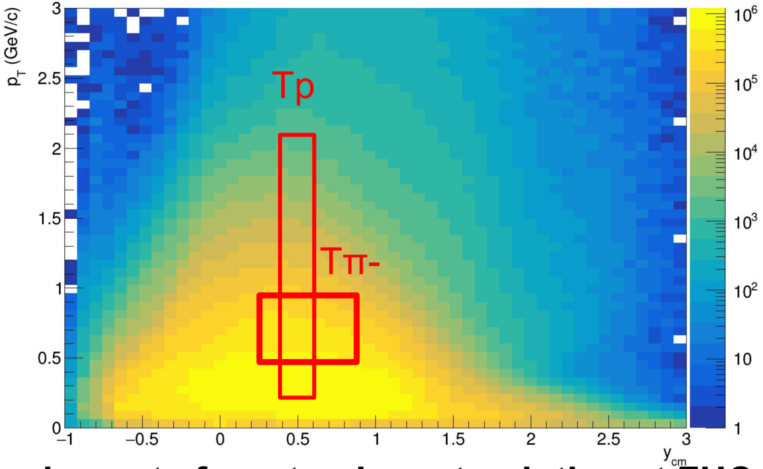

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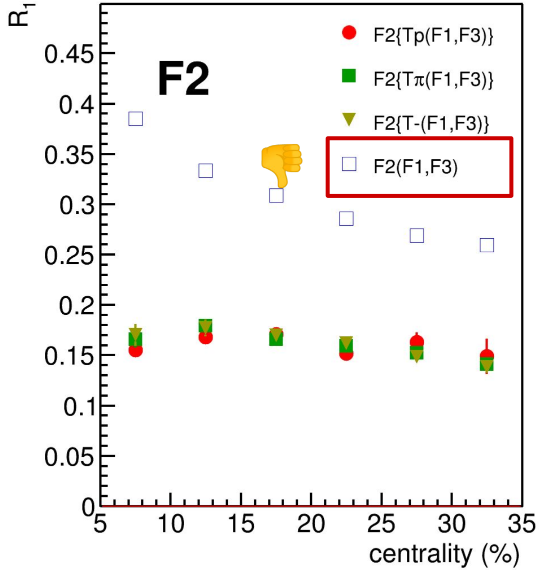

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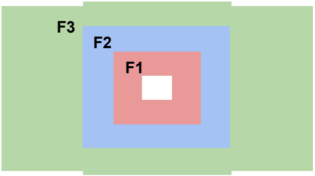
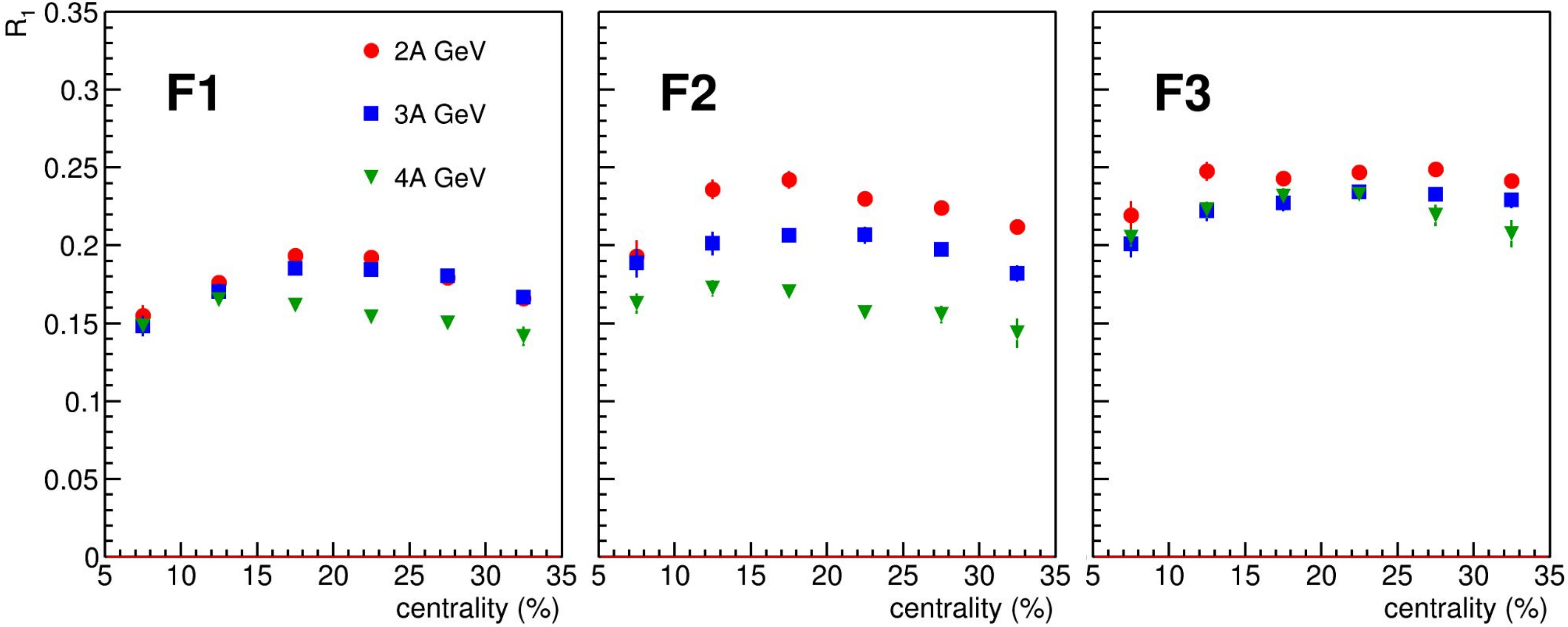
Symbol "F2{Tp}(F1,F3)" means R_1 calculated via (4S resolution):

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

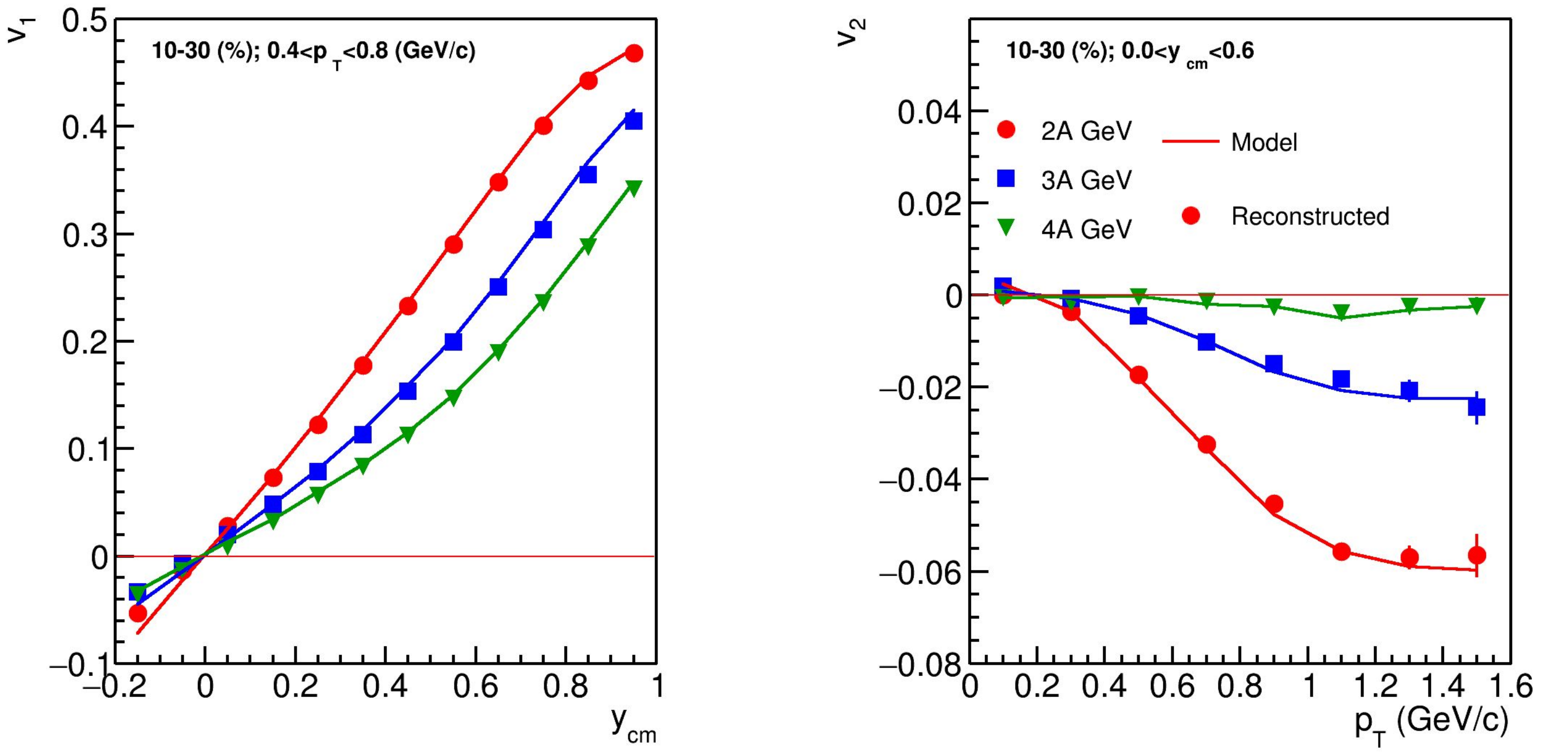
Rec R1: DCMQGCM-SMM Xe+Cs





Resolution is lower for higher energies due to lower v_1

Directed and elliptic flow in Xe+Cs (JAM)



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