Proton directed flow relative to the spectator plane in Ag+Ag collisions at 1.23A and 1.58A GeV with HADES

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HADES

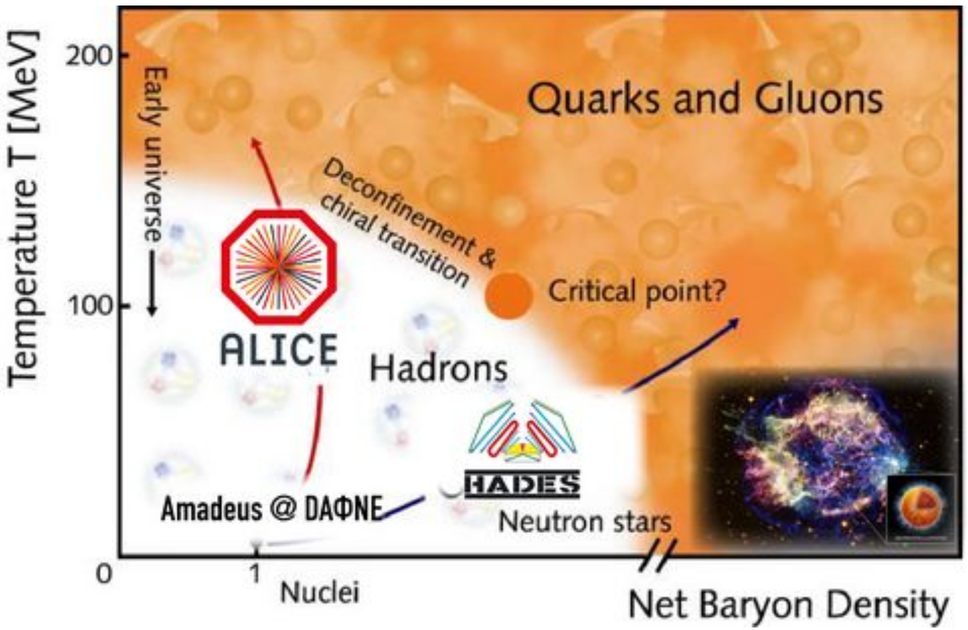
for the HADES Collaboration

НИЯУ МИФИ

NUCLEUS 2021 conference, 2021.09.20

GSI

Study of QCD phase diagram



Heavy-Ion collisions in HADES

(Nature Physics 15 (2019) 10, 1040)

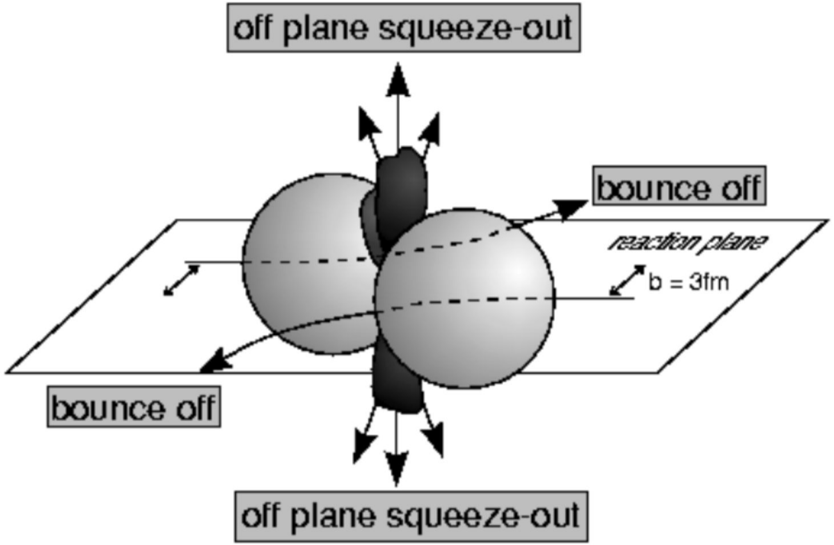
Temperature: ~ 70 MeV

Net Baryon Density: $> 3\rho_0$

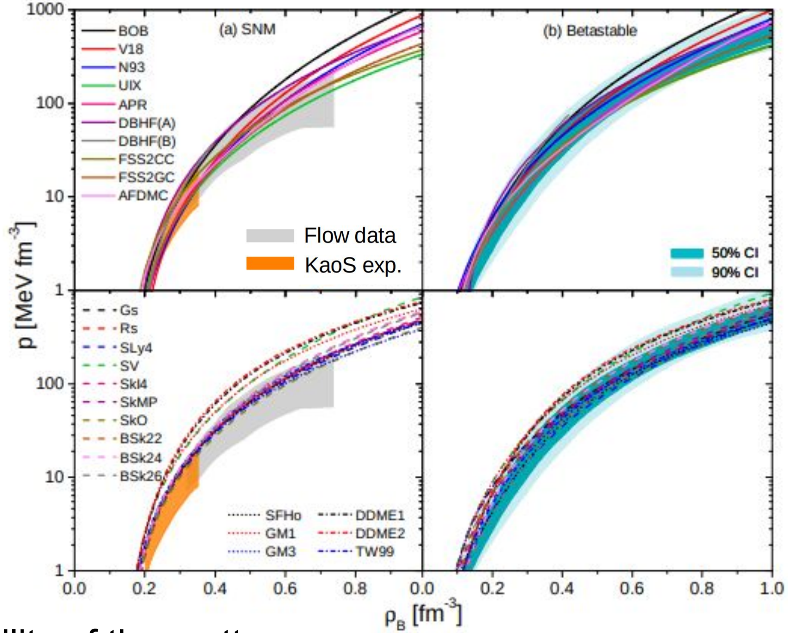
ρ_0 =110 MeV/fm·c^2 (nuclear ground state density)

Collective flow in heavy-ion collisions

spatial asymmetry of the initial energy distribution transforms into anisotropic emission of produced particles via interaction inside the overlapping region of colliding nuclei



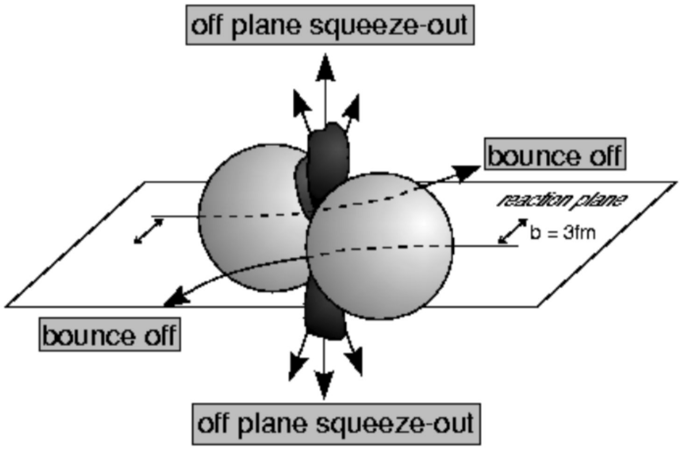
Symmetry 13 (2021) 3, 400



Anisotropic flow measurements can constrain compressibility of the matter created in the collision

Anisotropic flow & spectators

spatial asymmetry of the initial energy distribution transforms via interaction into anisotropic emission of produced particles



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

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

directed flow:

$$v_1 = \langle \cos\left(\varphi - \Psi_{RP}\right)\rangle$$

Flow vectors

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

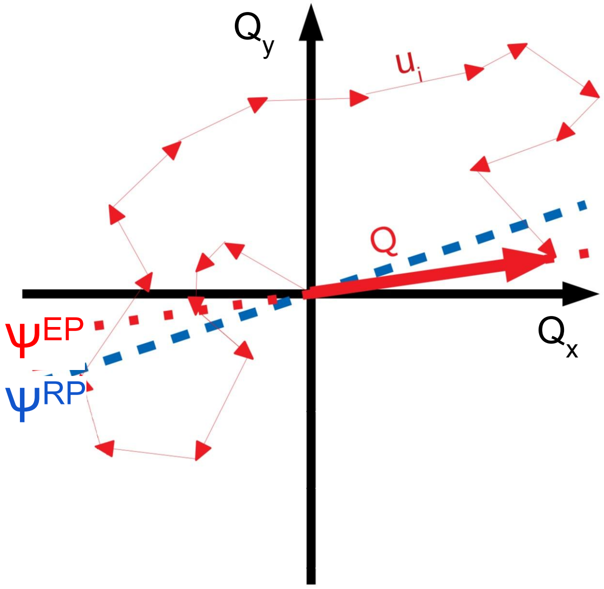
$$u_n = e^{in\phi}$$

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



Flow methods for v_n calculation

Classical method:
Used for cross-checks

Event plane (EP) method:

$$v_1 = \frac{\langle \cos(\phi - \Psi_1^{EP}) \rangle}{R_1}$$

Resolution correction with random subevent (RND):

$$R_1^{sub} = \sqrt{\langle \cos(\Psi_n^a - \Psi_n^b) \rangle}$$

Also checked:
extrapolation to full event plane resolution using method by J.Y. Ollitrault [arXiv:nucl-ex/9711003]

Modern approach:
Used in the proton analysis

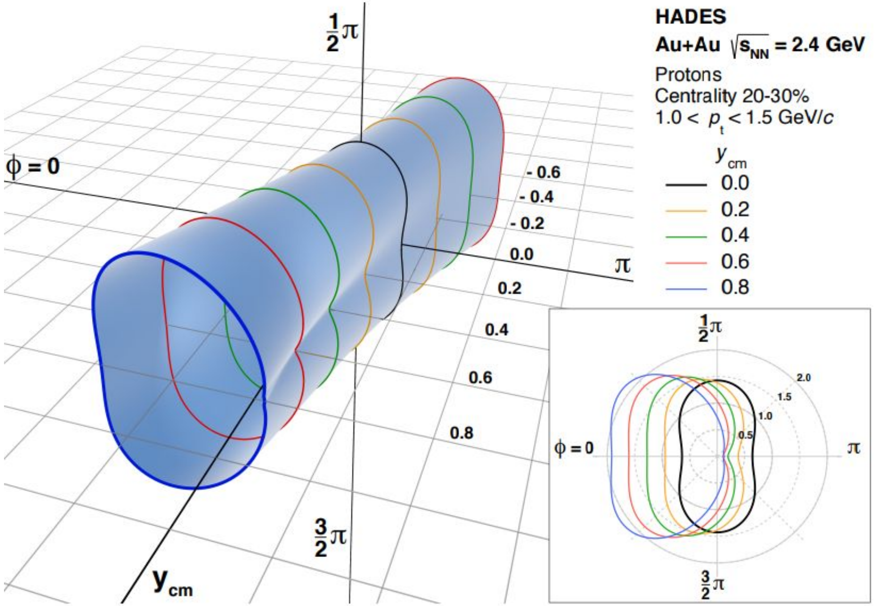
Scalar product (SP) method:

$$v_1 = \frac{\langle u_1^a Q_1^a \rangle}{R_1}$$

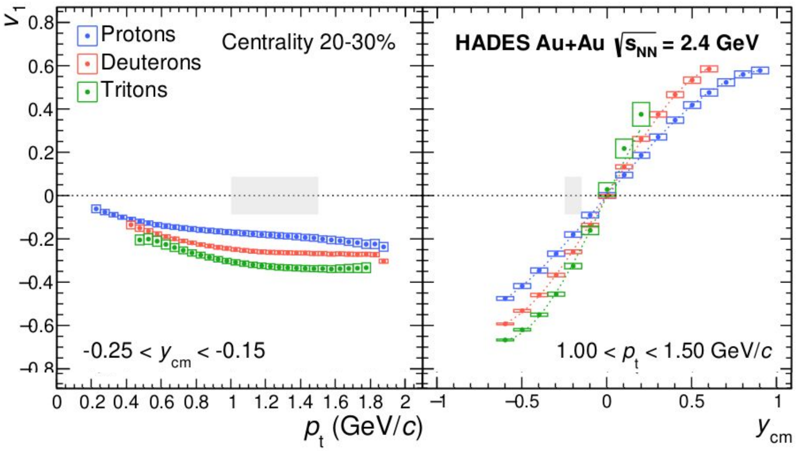
Where

$$R_1^a = \frac{\sqrt{\langle Q_1^a Q_1^b \rangle \langle Q_1^a Q_1^c \rangle}}{\sqrt{\langle Q_1^b Q_1^c \rangle}}$$

Anisotropic flow in Au+Au @ 1.23A GeV collisions



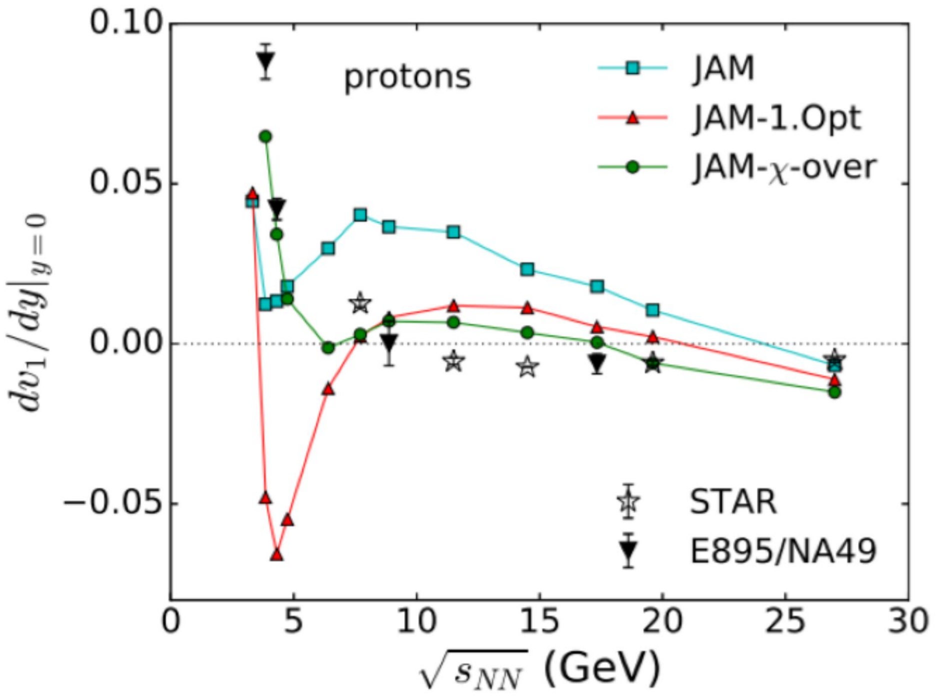
HADES Collaboration, Phys.Rev.Lett. 125 (2020) 262301



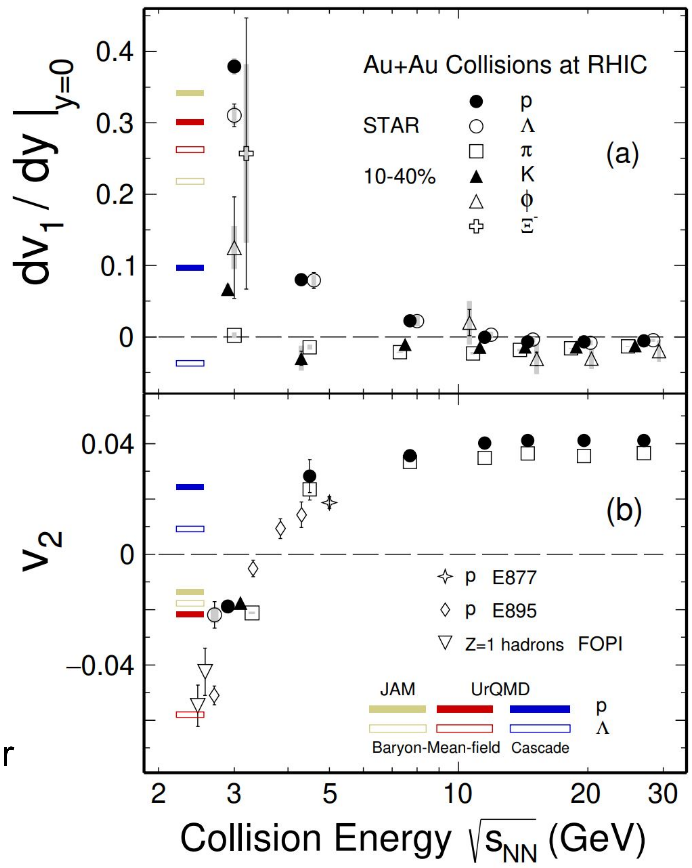
Anisotropic flow of protons and light nuclei is measured up to 6th harmonic in Au+Au@1.23A GeV

- Three-dimensional emission pattern is reconstructed
- Systematic uncertainty due to methods of symmetry plane estimation is obtained

dv_1/dy as the function of collision energy



arXiv:2108.00908v1 [nucl-ex]



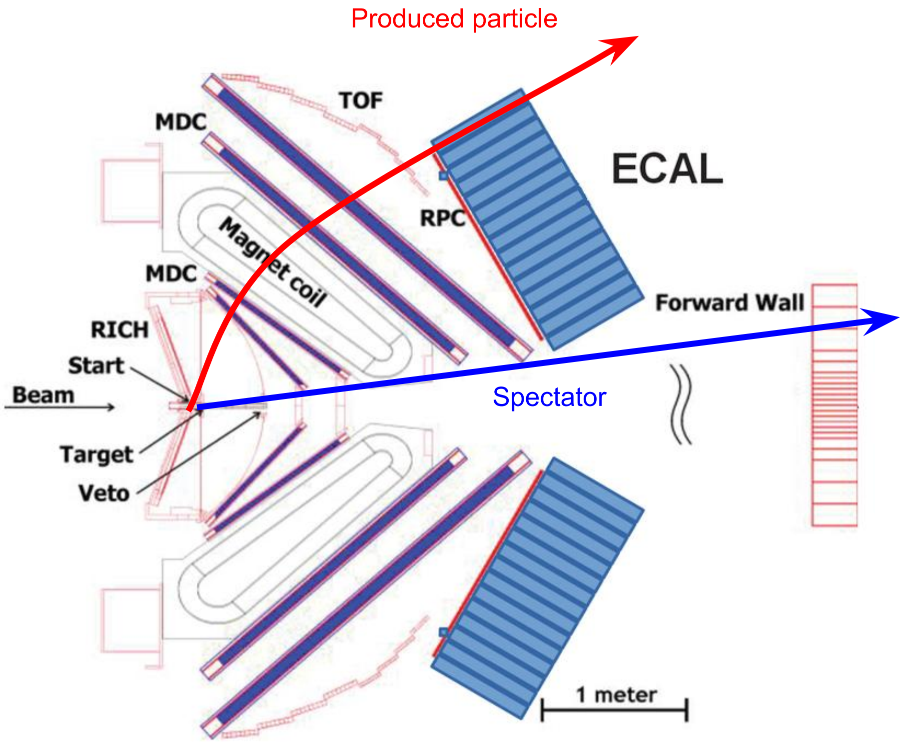
Directed flow is sensitive to equation of state of the matter created in the collision

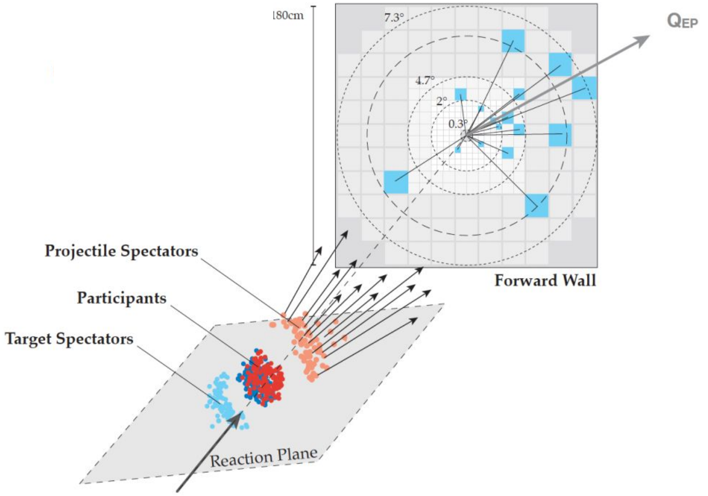
The HADES@SIS 18 (GSI, Germany)

2012: Au+Au @ E_{lab}=1.23A GeV 7×10^9

2019: Ag+Ag @ E_{lab}=1.23A GeV 7×10^9

@ E_{lab}=1.58A GeV 14×10^9





Reaction plane estimation using the deflection of projectile spectors

Q-vectors for protons and charged fragments

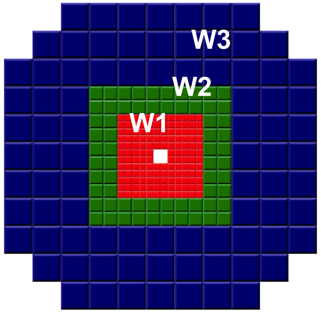
Protons with $p_T < 2$ GeV/c

for 2 rapidity regions:

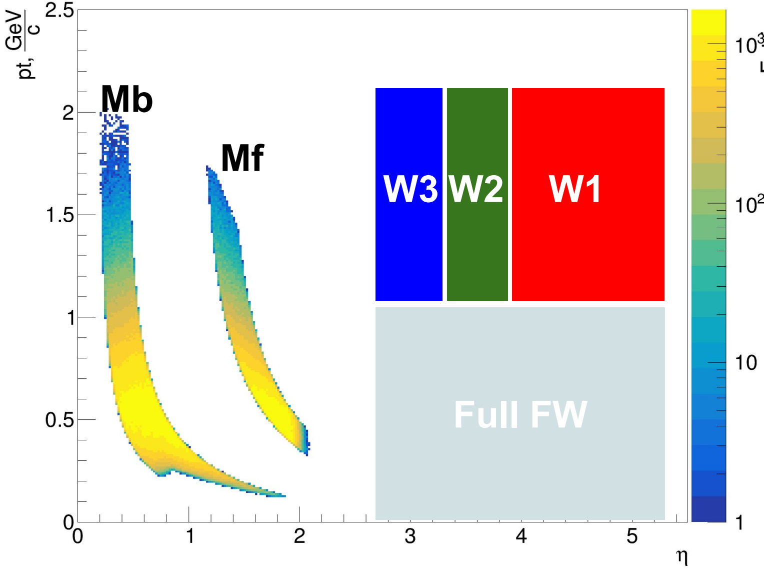
- Mf — y_{cm} [0.35, 0.55]
- Mb — y_{cm} [-0.55, -0.35]

Charged fragments from FW:

W1: $3.77 < \eta < 5.38$
W2: $3.28 < \eta < 3.88$
W3: $2.68 < \eta < 3.35$



Rapidity coverage of different subevents

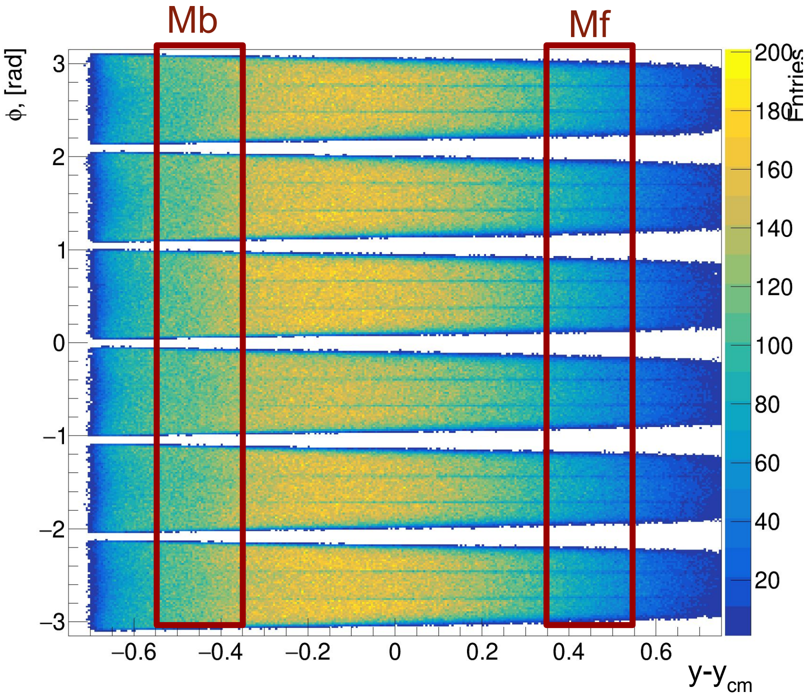


Full FW (sum over all modules) $2.68 < \eta < 5.38$

RND-sub: all modules randomly splitted into 2 groups

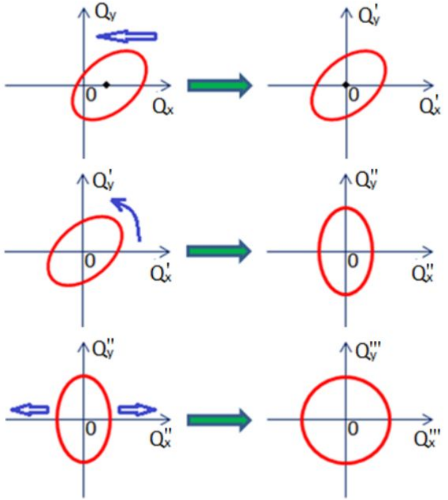
Azimuthal asymmetry of the HADES acceptance

ϕ-Rapidity yield of protons



Required corrections to reduce effects of non-uniform azimuthal acceptance

1. Recentering
2. Twist
3. Rescaling



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

QnTools framework

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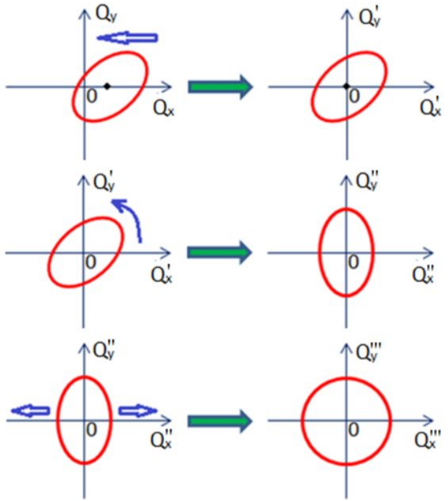
I. Selyuzhenkov and S. Voloshin PRC77, 034904 (2008)

Originally implemented as QnCorrections framework for ALICE experiment at CERN:
J. Onderwaater, I. Selyuzhenkov, V. Gonzalez

QnTools analysis package:
https://github.com/HeavyIonAnalysis/QnTools

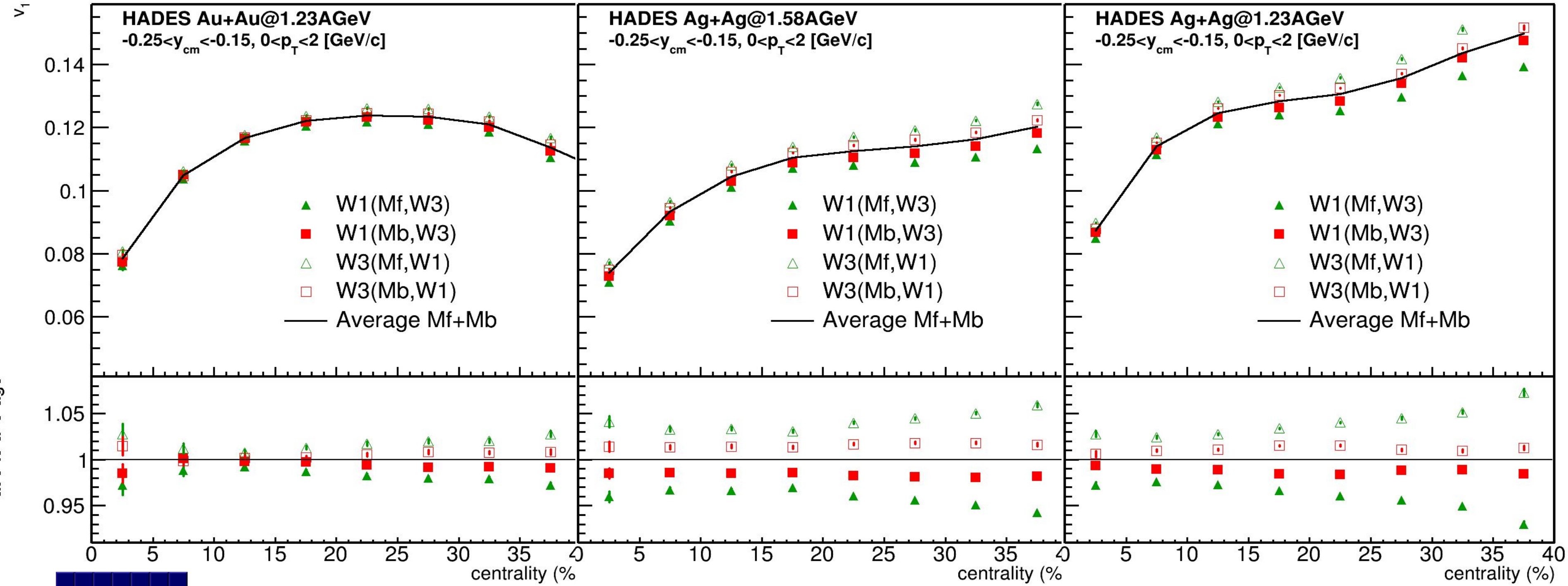
1. Recentering
2. Twist
3. Rescaling

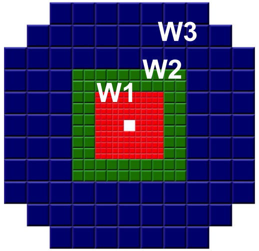


QnTools configuration

Q-vector	Q_n weight	Correction axes	Correction steps	Error calculation	Q_n Normalization
Protons	1	p_T [0.0, 2.00], 10 bins y_{cm}[-0.75, 0.75], 15 bins Centrality, 8 bins	Recentering Twist Rescaling	Bootstrapping, 100 samples	Sum of Weights
Charged Fragments	Module charge	Centrality, 8 bins	Recentering Twist Rescaling		

Results for rapidity separated sub-events

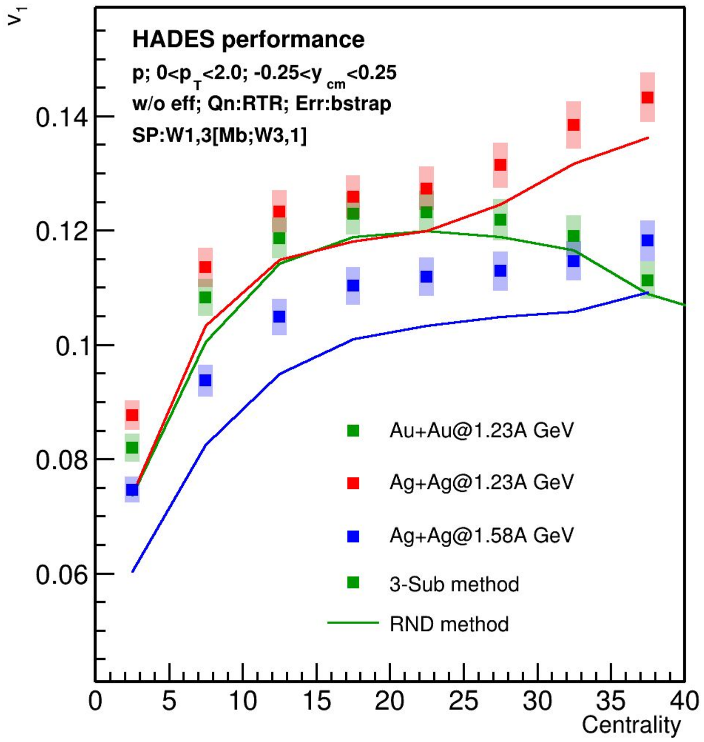




Combinations with Mb are consistent with each other within 3-5%

In the further analysis the average of W1(Mb, W3) and W3(Mb, W1) will be used

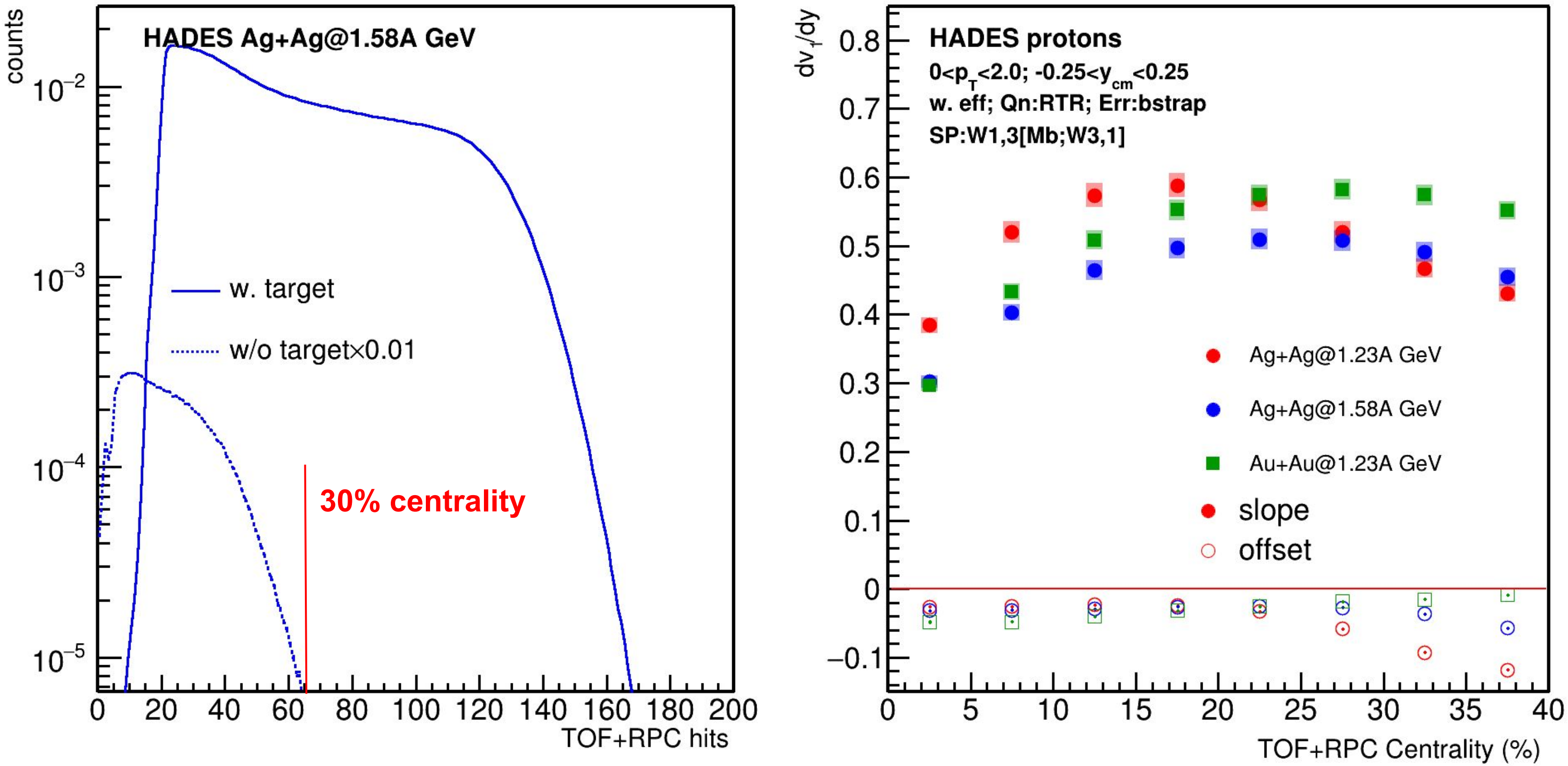
Evaluation of systematic uncertainties



Investigated sources of uncertainties:

- Method of flow calculation
- Non-flow correlations
- Occupancy effects
- Efficiency correction
- Selection criteria
- Azimuthal detector non-uniformity

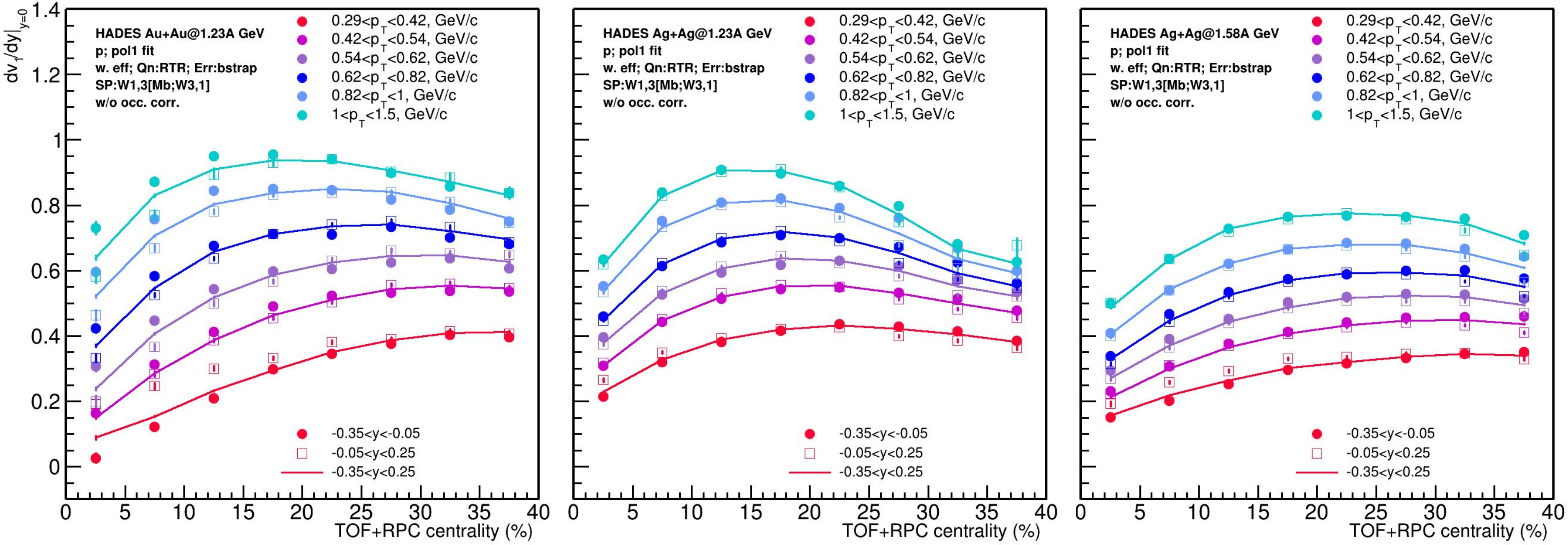
Systematics due to Ag+C contamination



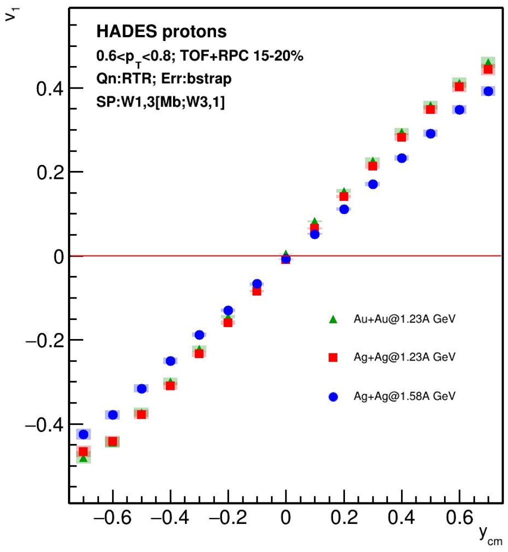
dv_1/dy: y>0 vs. y<0 in p_T bins

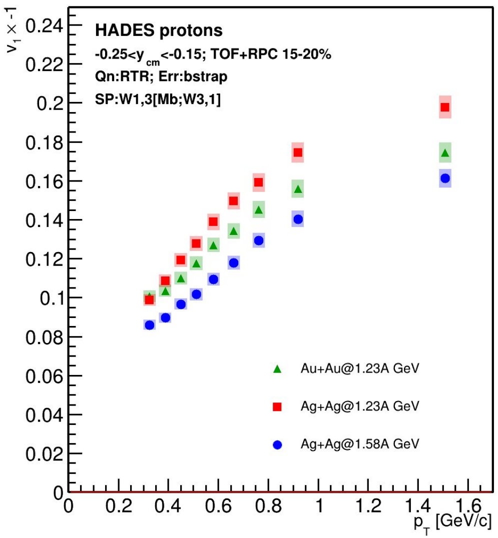
Open: -0.35<y<-0.05
Full: -0.05<y<0.25
Fit: pol1 in 3 bins 0.25<|y|<0.05

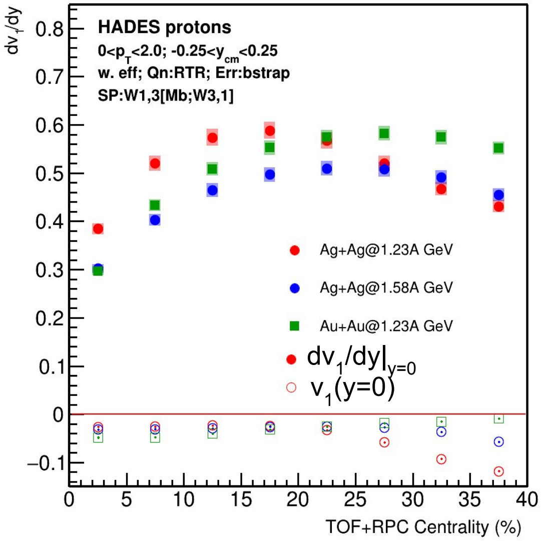
Au+Au@1.23A Gev | Ag+Ag@1.23A Gev | Ag+Ag@1.58A Gev



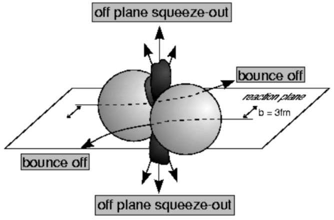
Proton v_1 vs y, p_T and centrality



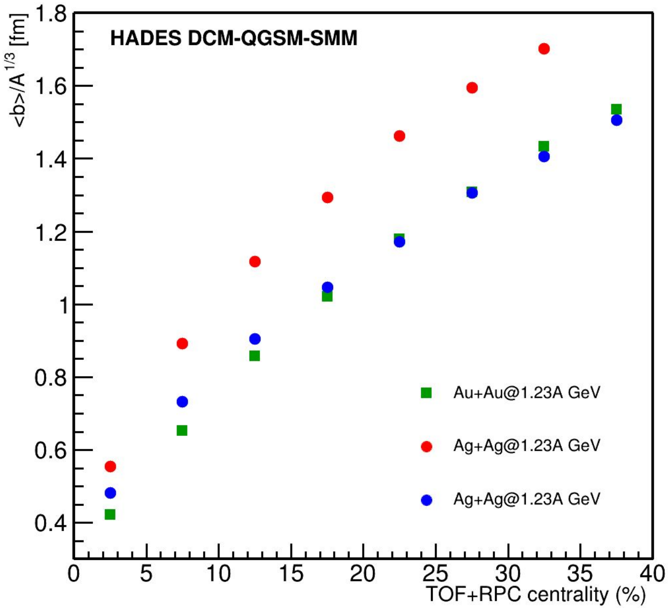


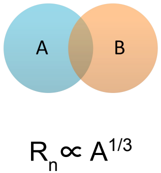


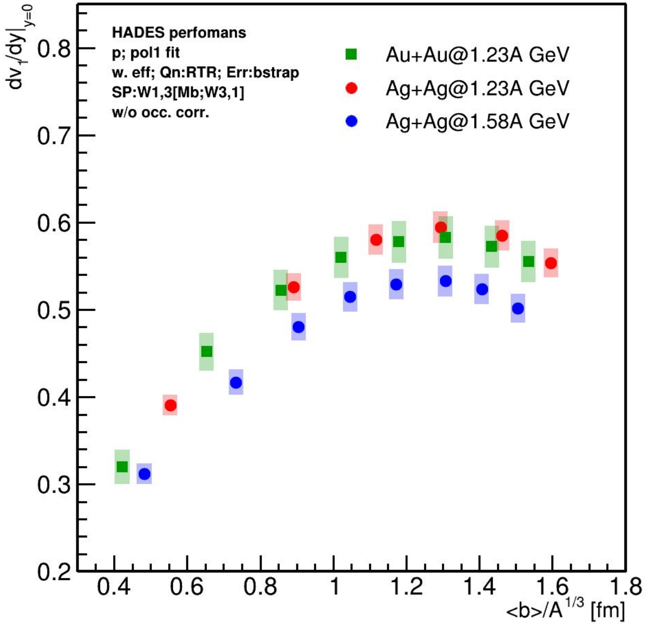
- Produced protons are deflected the same way as spectator fragments ($dv_1/dy > 0$)
- For the same collision system size (Ag):
  dv_1/dy becomes weaker due to less time of interaction between spectators and overlapping region



dv_1/dy system size dependence

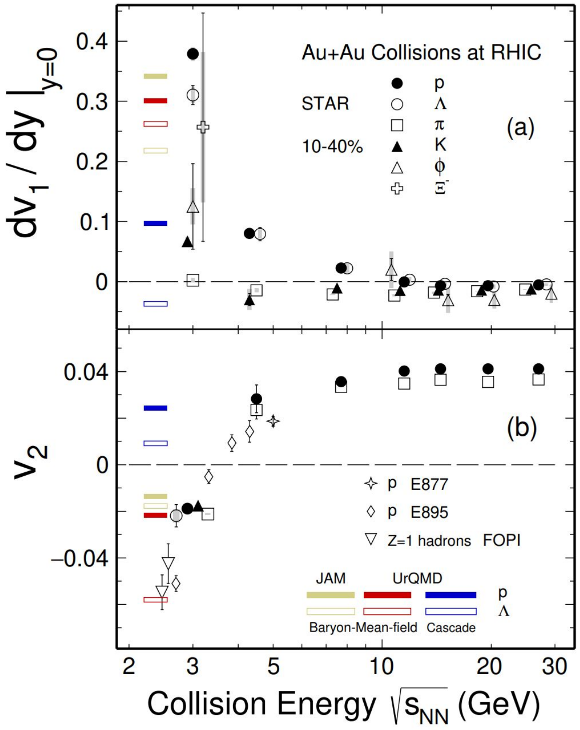




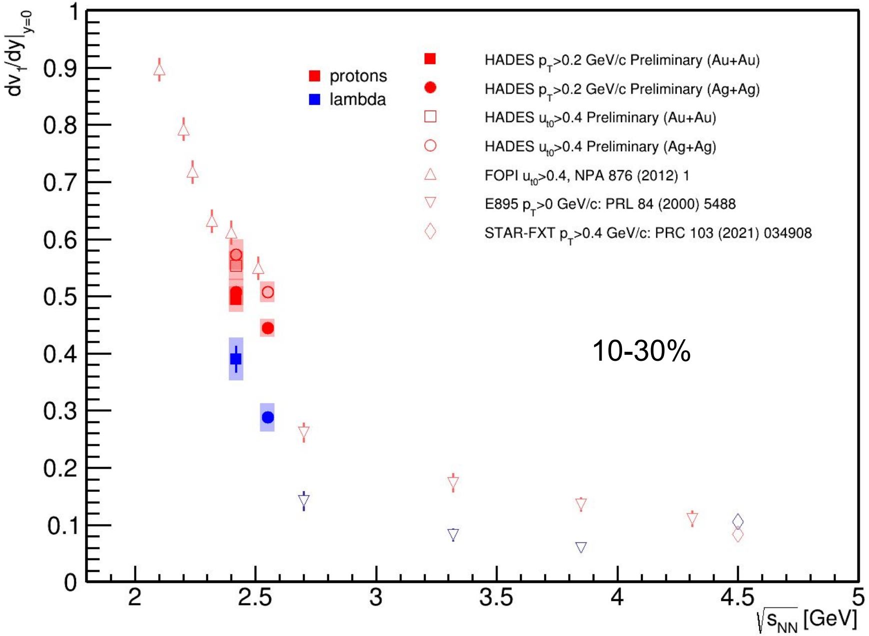


dv_1/dy does not depend on the size of colliding nuclei but on the shape of overlapping region(~ $b/A^{1/3}$)

Slope at midrapidity (dv_1/dy) vs. $\sqrt{s_{NN}}$: protons vs. Λ hyperon



v_1 of Lambda's: see Kornas, Galatyuk, Selyzhenkov at SQM-2021



HADES results follow the energy dependence of the FOPI data

Summary

- Directed flow of protons is measured in Au+Au@1.23A GeV, Ag+Ag@1.23A GeV and Ag+Ag@1.58A GeV collisions
- Systematic uncertainty due to residual non-flow correlations is observed to be 3-5% measurement relatively to the spectators symmetry plane
- Produced protons are deflected to the same direction as spectator fragments
- For the same collision energy the slope of directed flow dv_1/dy depends only on the shape of overlap region
- The slope of directed flow dv_1/dy is lower at higher collision energy for same system size.

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Backup