Performance of the CBM experiment at FAIR for measurement of charged hadron anisotropic flow

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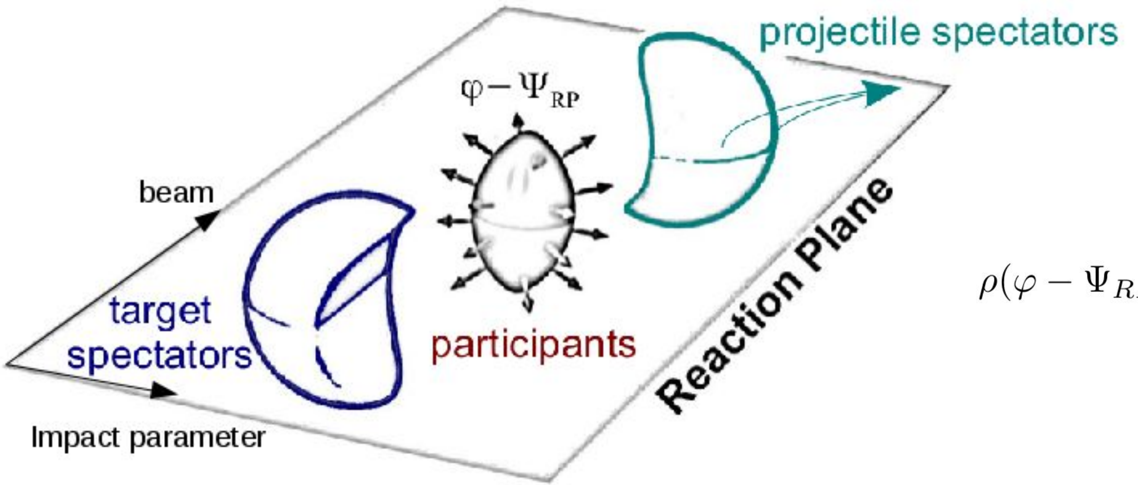
NUCLEUS 2021 Conference

Collision geometry and anisotropic transverse flow



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

$$\Downarrow$$

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

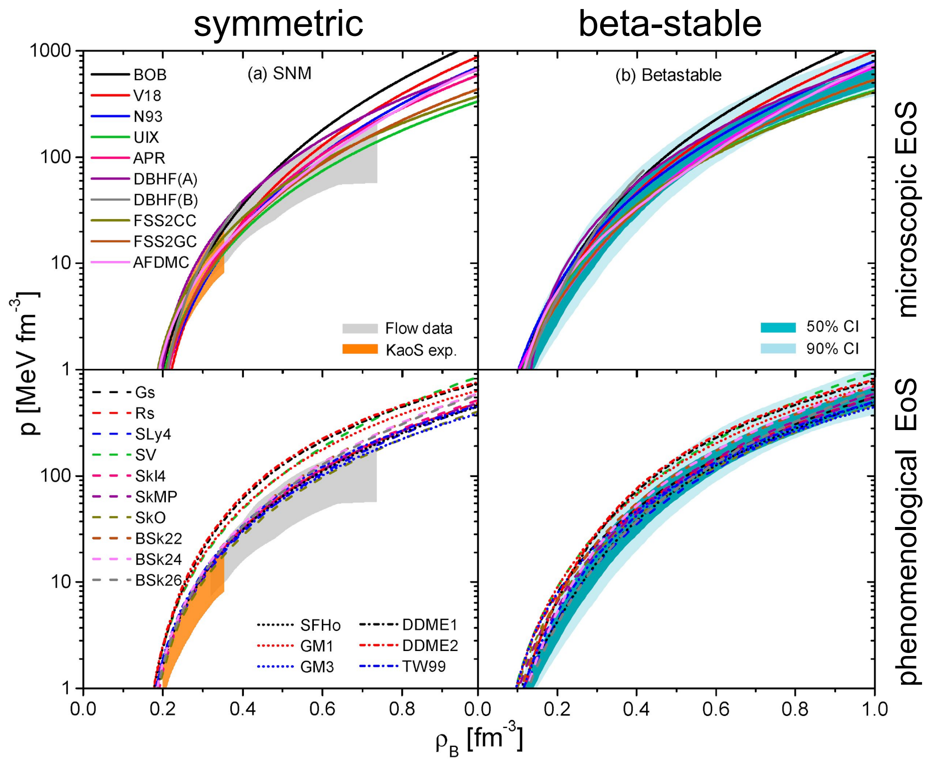
Asymmetry in coordinate space converts

(due to interaction & depending on the properties created matter)

into momentum asymmetry with respect to the collision symmetry plane

Anisotropic transverse flow in study of QCD matter

Pressure vs. baryon density



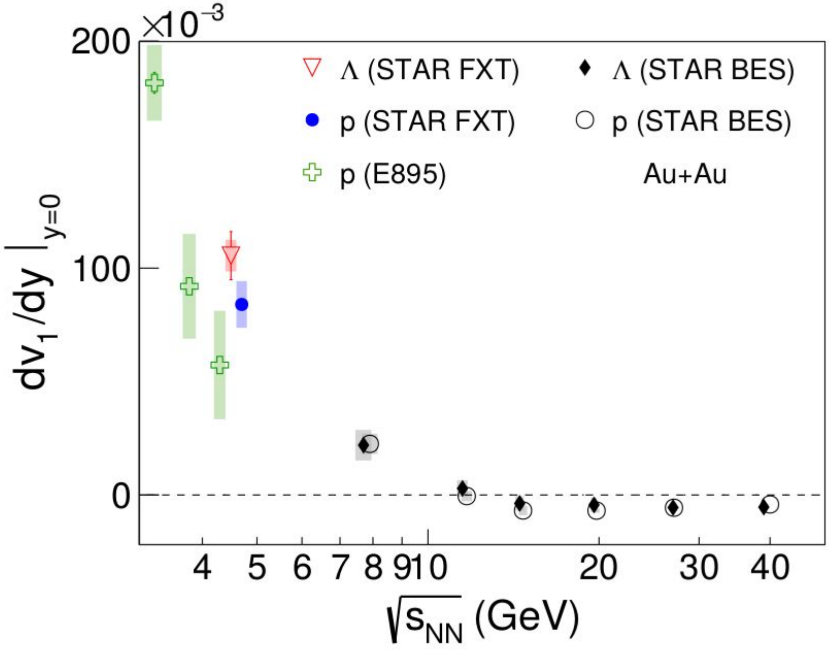
Measurements of anisotropic flow constrain the transport coefficients and equation of state (EoS) of the matter created in heavy ion collisions

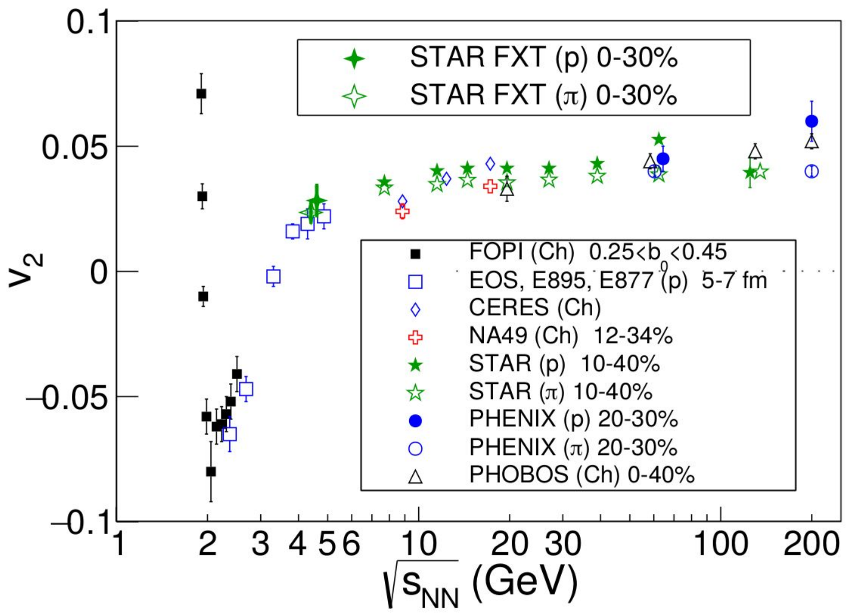
orange KaoS experiment
grey Flow data
blue GW170817 limits

G. Burgio et al., Symmetry 13(3), 400 (2021)

Collective flow at FAIR energies

STAR Collaboration, arXiv:2007.14005 (+ new preliminary at CPOD2021 for Au+Au@3GeV by S. Lan)





CBM will extend existing data and provide new measurements for identified charged hadrons, di-leptons and multistrange hyperons at $\sqrt{s_{NN}} = 2.7 - 4.9$ GeV

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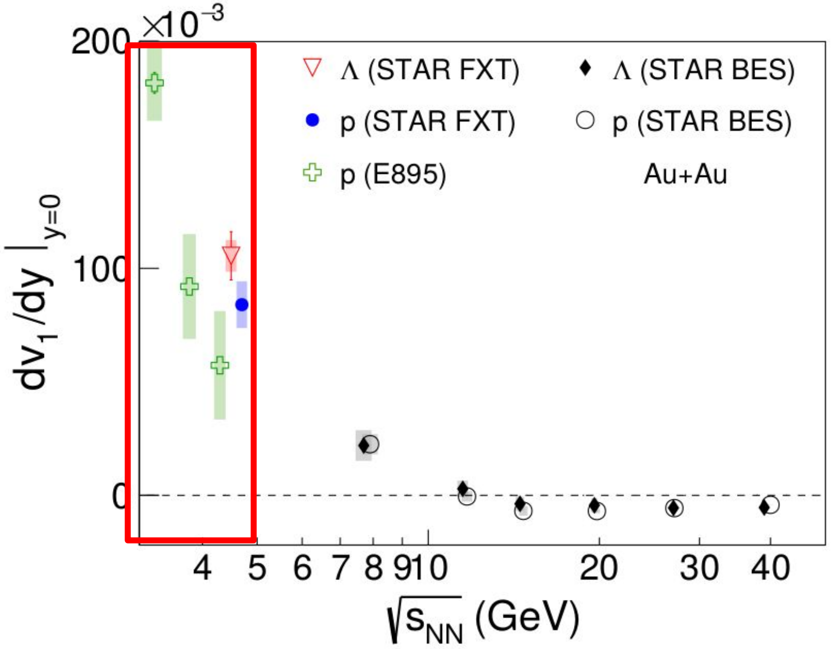

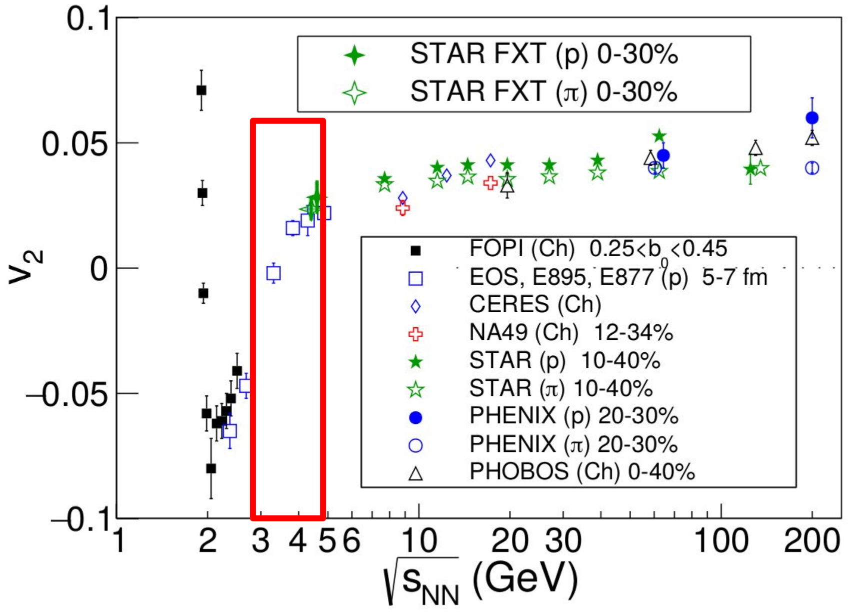

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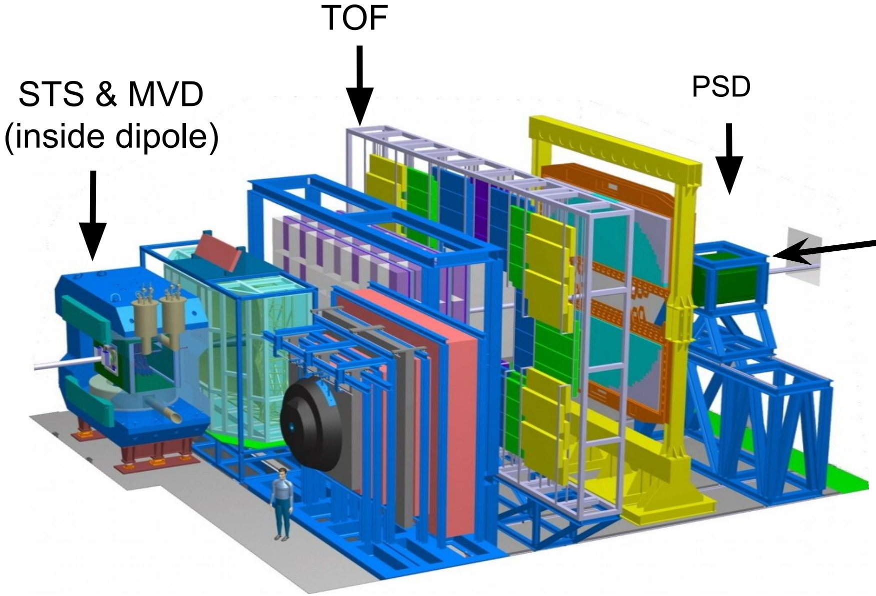
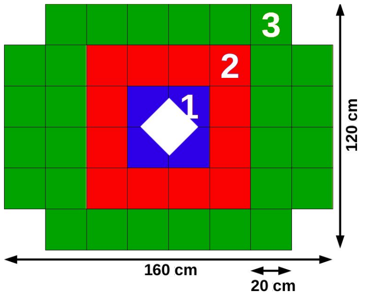
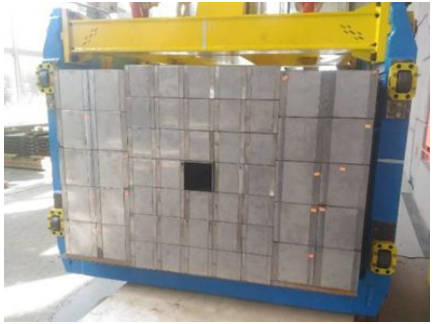
CBM subsystems used for flow studies



Projectile Spectator Detector



FAIR-PHASE0: BM@N FHCal

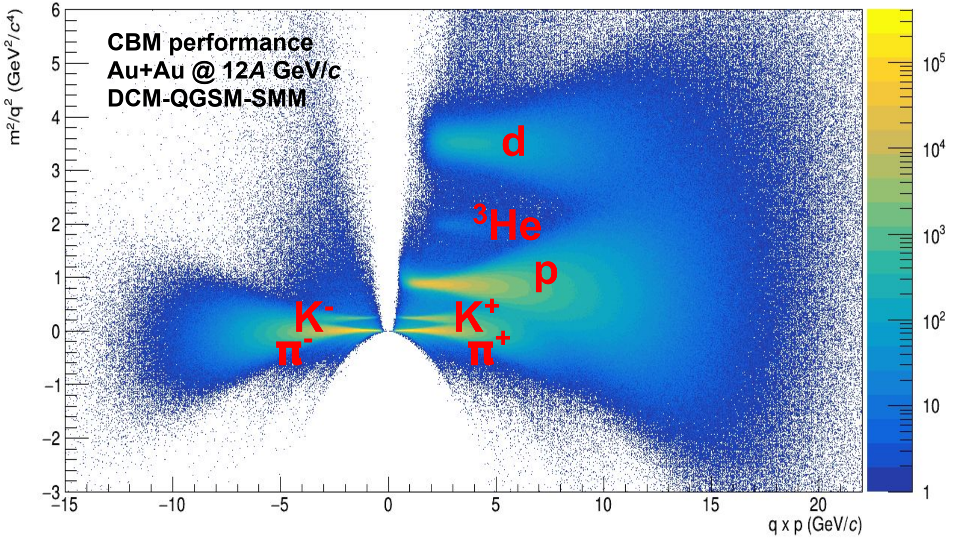


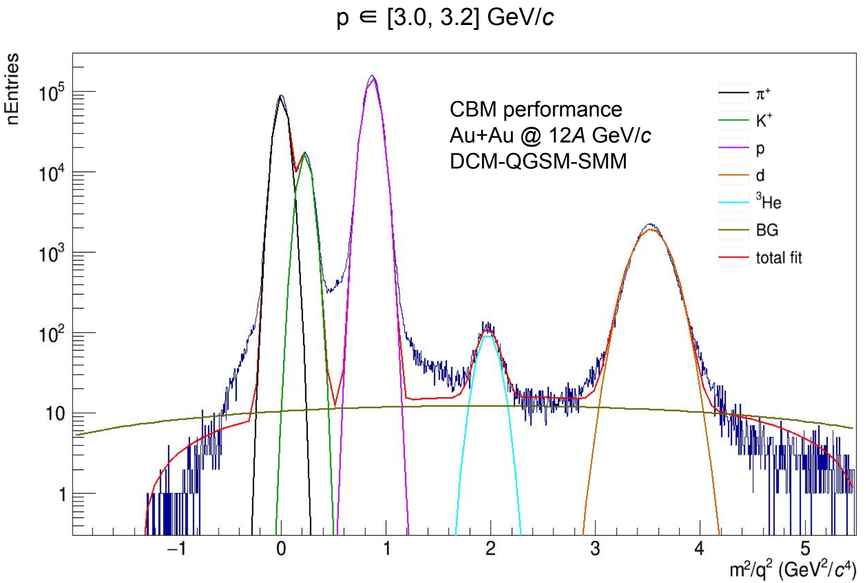
- Hadron kinematics (φ, y, p_T): STS+MVD tracking
- Centrality estimation: STS multiplicity
- Particle identification: Bayesian TOF
- Reaction plane (Ψ_{RP}): PSD transverse energy; φ distribution in STS

Simulation setup

Model	DCM-QGSM-SMM (with fragments)
System	Au+Au
Beam momentum	12*A* GeV/*c*
Statistics	5M events
CBM subsystems	MVD, STS, RICH, TDR, TOF, PSD
PSD geometry	20 cm hole size 44 modules
Transport code	GEANT4
Detector response & reconstruction	CbmRoot APR20

Bayesian charged hadron identification with TOF

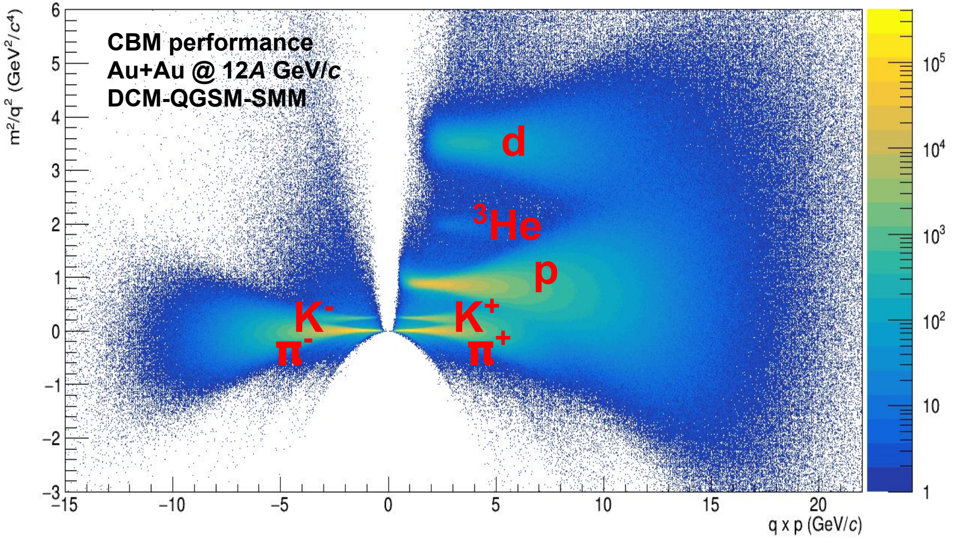


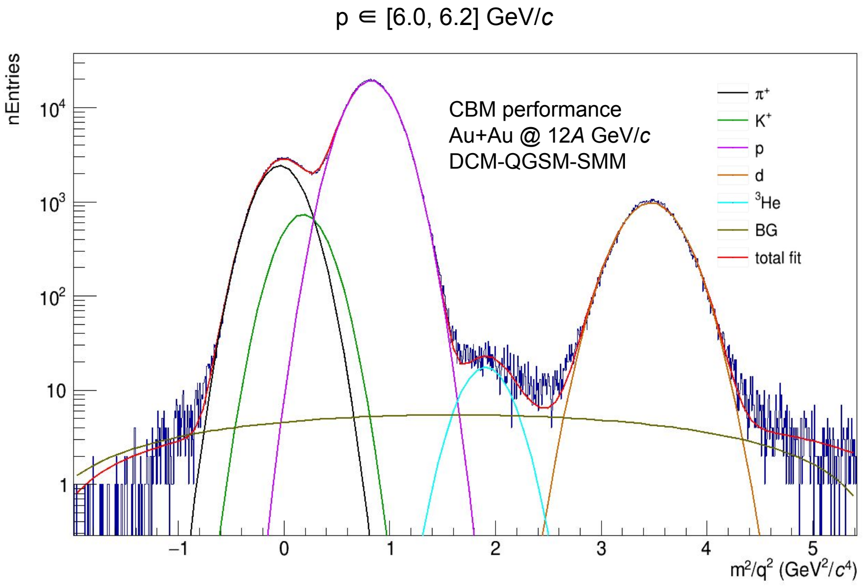


$$\frac{m^2}{q^2} = p^2\left(\frac{t^2c^2}{l^2} - 1\right)$$

- Time-of-Flight information provides clear separation between charged hadrons
- Background is dominated by mismatch between tracks and TOF hits

Bayesian charged hadron identification with TOF





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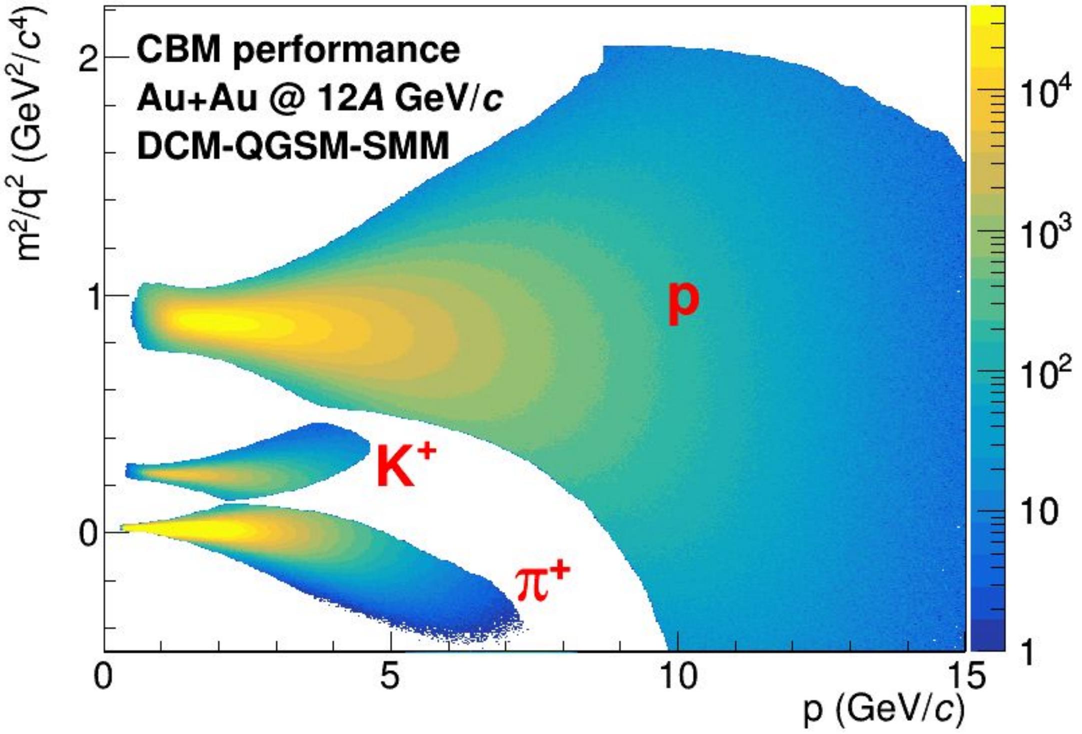
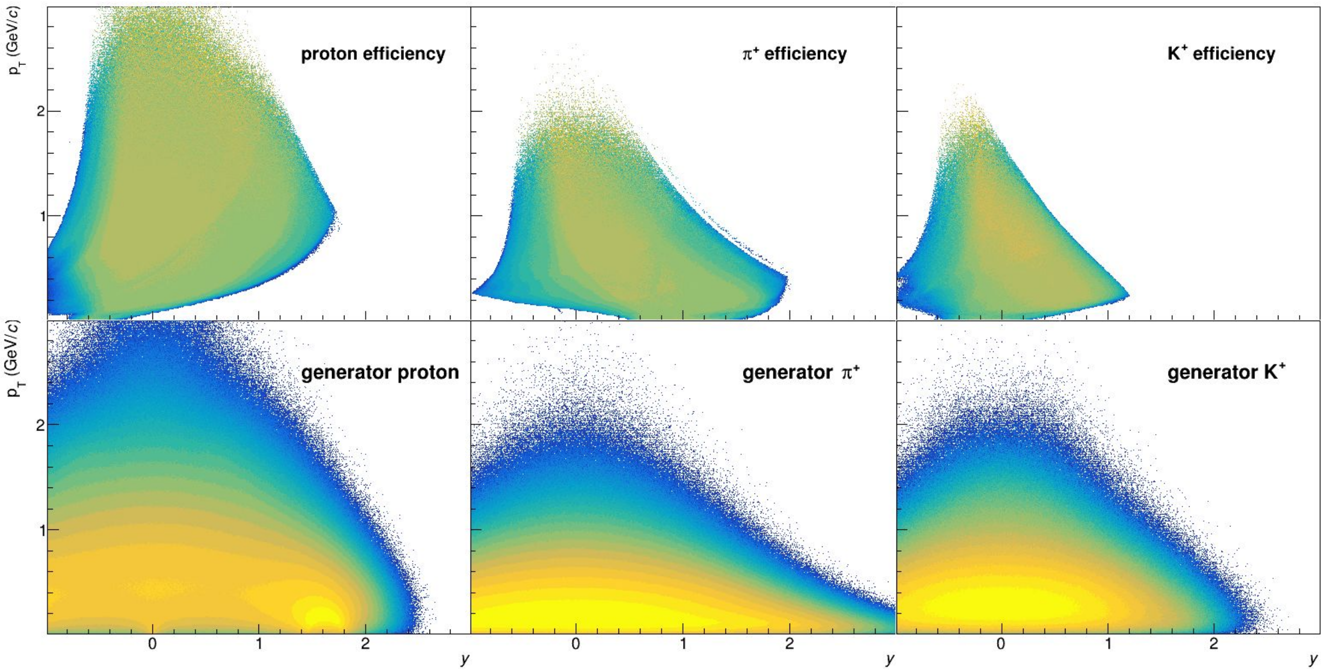
Bayesian selection of π^+, K^+ and protons



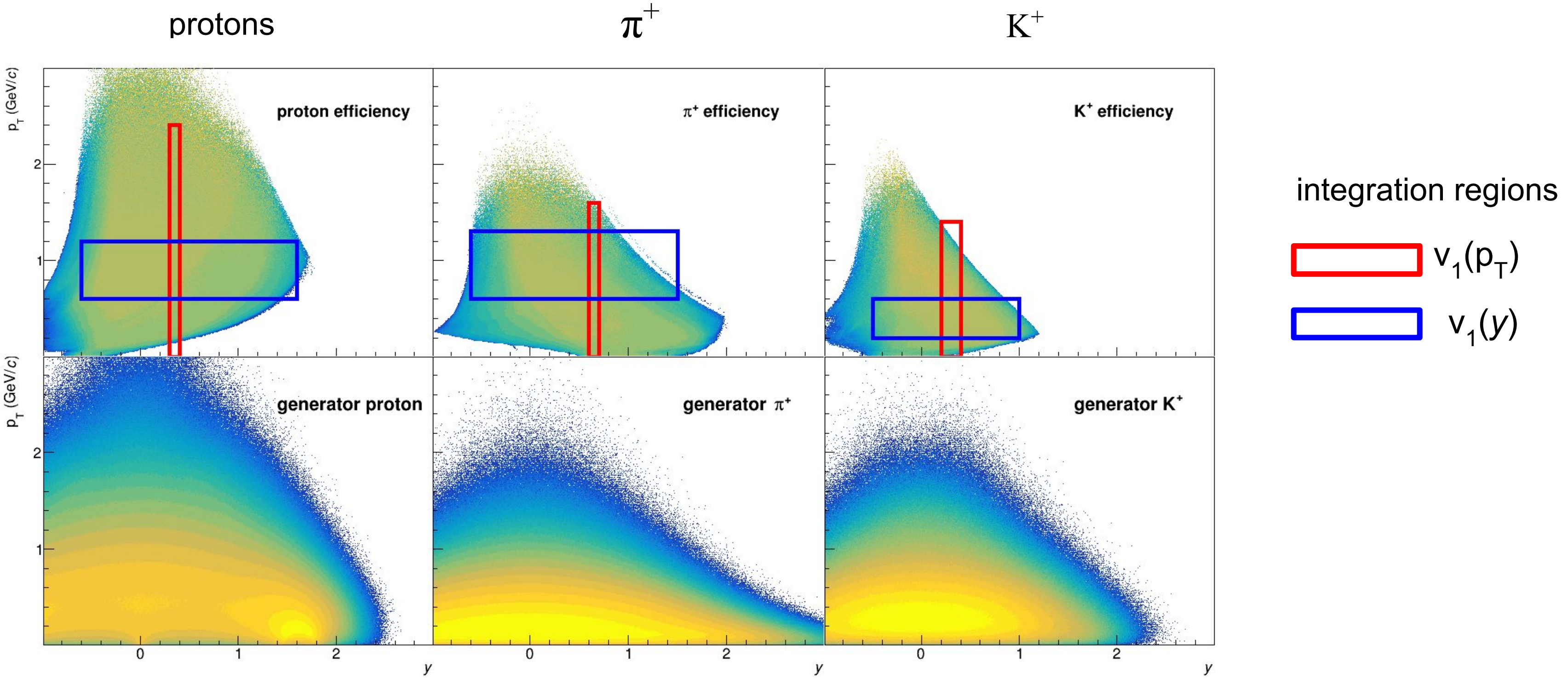
Proton, K^+ and π^+ selection with 90% purity requirement

Acceptance & efficiency maps: proton, π^+, and K^+

protons π^+ K^+



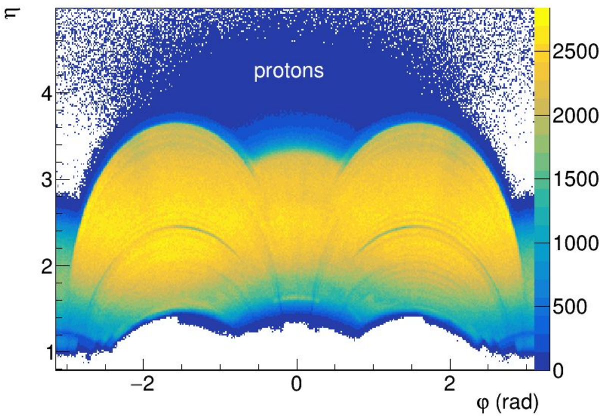
Acceptance & efficiency maps: proton, π^+, and K^+



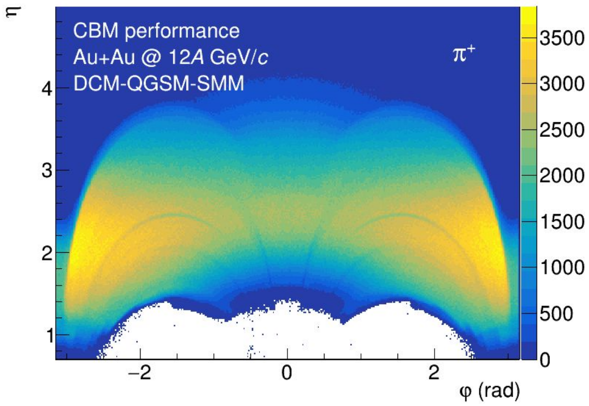
- this presentation: (p_T, y)-differential v_1 results are studied for kinematic regions with high efficiency
- in progress: efficiency-corrected results for other regions

Azimuthal non-uniformity of the CBM response

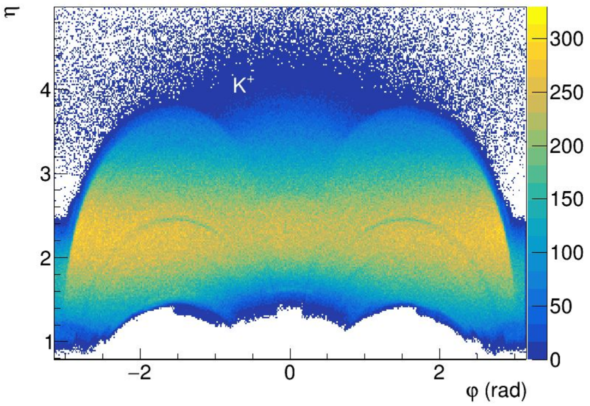
protons

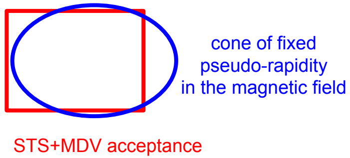


π^+



K^+





Distributions reflect rectangular structures of the STS, MVD & TOF detectors

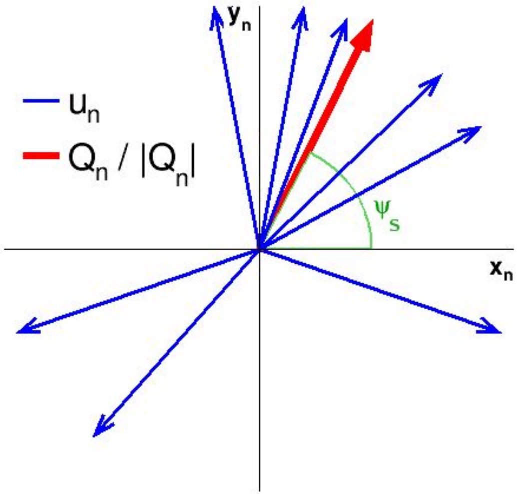
Azimuthal non-uniformity of the CBM detectors response requires multi-differential (p_T, y, centrality) corrections

Scalar product method for v_n measurement

u and **Q**-vectors:

$$\mathbf{u_n} = \{u_{n,x}, u_{n,y}\} = \{\cos n\phi, \sin n\phi\}$$

$$\mathbf{Q_n} = \{Q_{n,x}, Q_{n,y}\} = \frac{1}{\sum_k w^k}\left\{\sum_k w^k u^k_{n,x}, \sum_k w^k u^k_{n,y}\right\}$$



Scalar product method:

v_n with respect to symmetry plane Ψ_S estimated using group of particles "*a*":

$$v^a_{1,i}(p_T, y) = \frac{2\langle u_{1,i}(p_T, y) Q^a_{1,i}\rangle}{R^a_{1,i}}, \ i = x, y.$$

$R^a{}_{1,i}$ is a 1st order event plane resolution correction (details in the following slides)

QnTools: Flow corrections and analyses framework

Data driven corrections procedure for azimuthal acceptance non-uniformity
I. Selyuzhenkov and S. Voloshin, PRC77 034904 (2008)

- Originally developed for ALICE
- Based on QnCorrections Framework (J. Onderwaater, V. Gonzalez, I. Selyuzhenkov)
- Extended for p_T/y - differential non-uniformity corrections
- Multi-dimensional flow vector based correlation analysis (L. Kreis and I. Selyuzhenkov)

https://github.com/HeavyIonAnalysis/QnTools

QnTools configuration:

- Corrections: Recentering, twist, and rescaling
- As a function of (p_T, y) and centrality

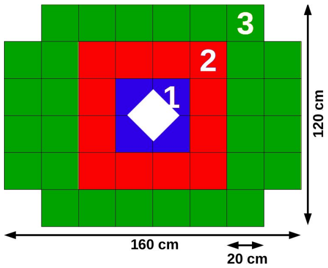
Resolution correction factor with 4-subevent method

$$R_{1,i}^{PSD1(3)} = \sqrt{\frac{\langle Q_{1,i}^{PSD1} Q_{1,i}^{PSD3} \rangle R_{1,i}^{STS}\{PSD1, PSD3\}}{\langle Q_{1,i}^{PSD3(1)} Q_{1,i}^{STS} \rangle}},$$

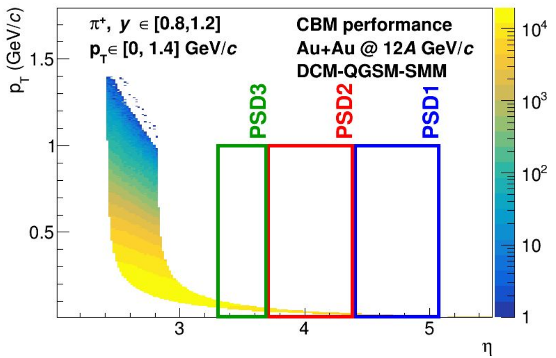
$$R_{1,i}^{PSD2} = \sqrt{\frac{\langle Q_{1,i}^{PSD2} Q_{1,i}^{STS} \rangle}{R_{1,i}^{STS}\{PSD1, PSD3\}}}, \qquad i = x, y$$

Use correlations between rapidity-separated subevents

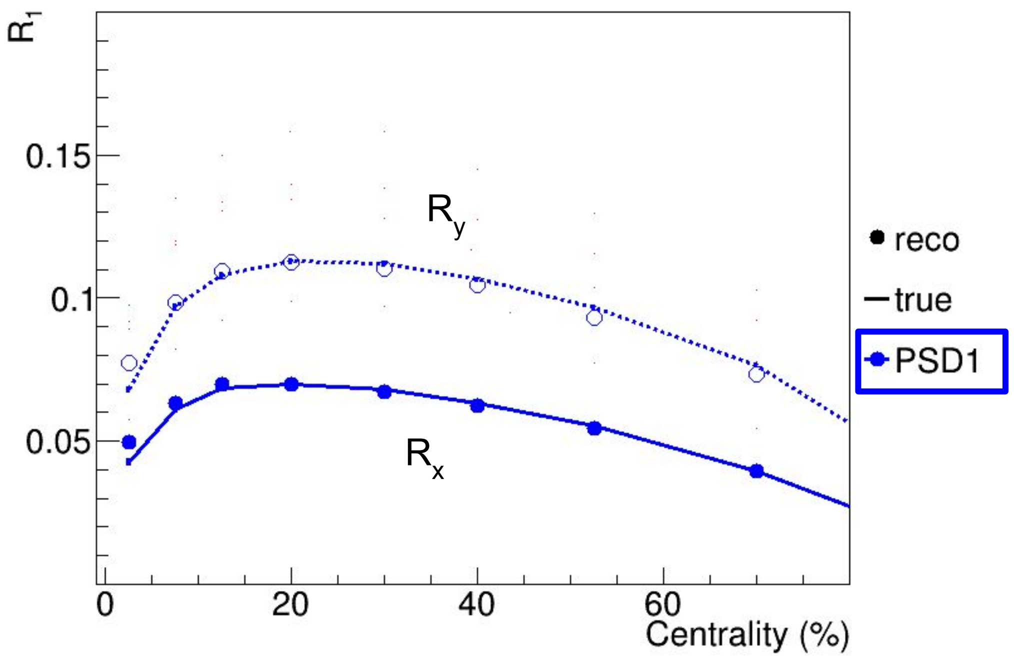
3 subevents from PSD



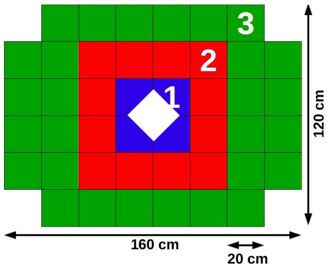
4th subevent from positive pions



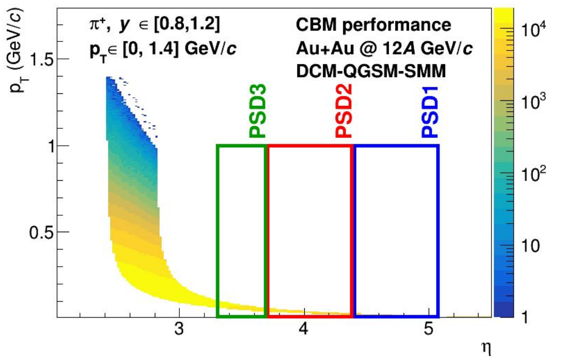
Resolution correction factor with 4-subevent method



3 subevents from PSD

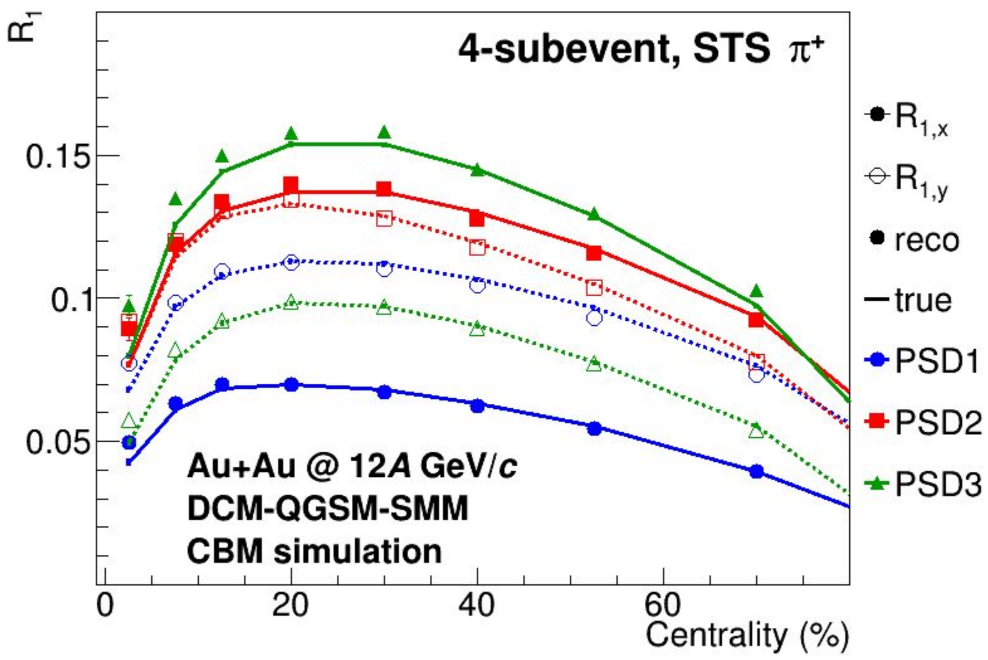


4th subevent from positive pions

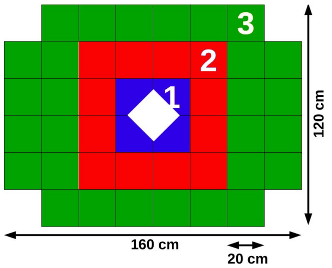


The data driven method reproduces the true PSD subevent resolution

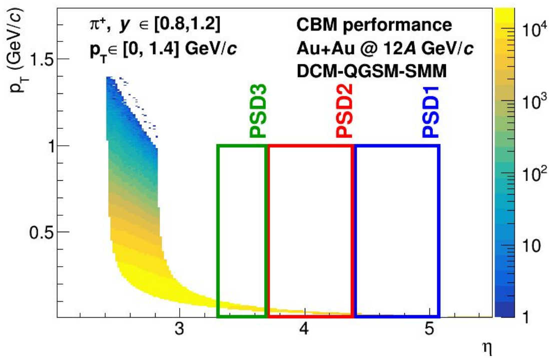
Resolution correction factor with 4-subevent method



3 subevents from PSD



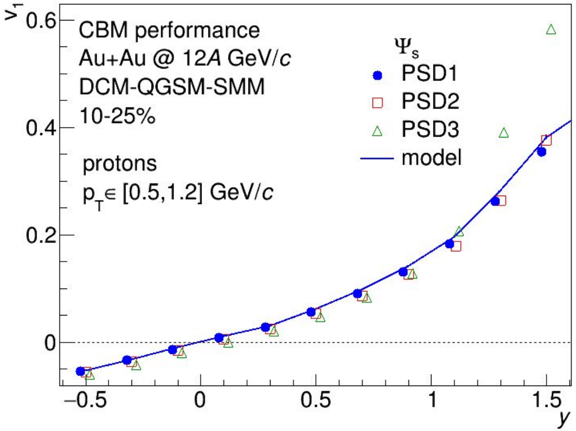
4th subevent from positive pions

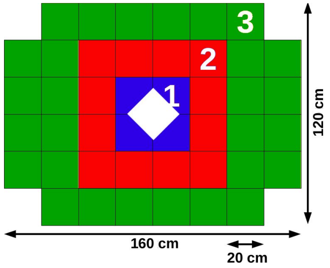


The data driven method reproduces the true PSD subevent resolution

v_1 of protons, π^+ and K^+ vs. rapidity

Bayesian proton selection

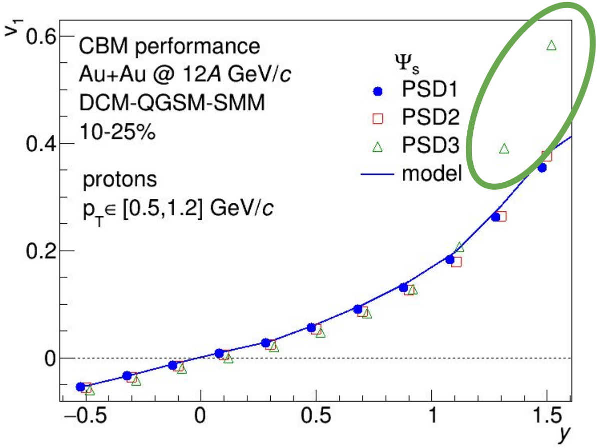




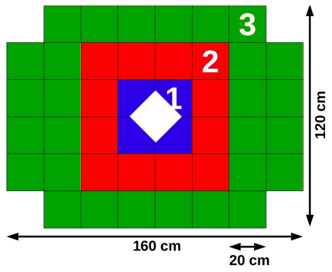
Results agree with the input v_1 for TOF-identified protons

v_1 of protons, π^+ and K^+ vs. rapidity

Bayesian proton selection



Acceptance overlap
of low p_T proton
for STS & PSD3



Results agree with the input v_1 for TOF-identified protons
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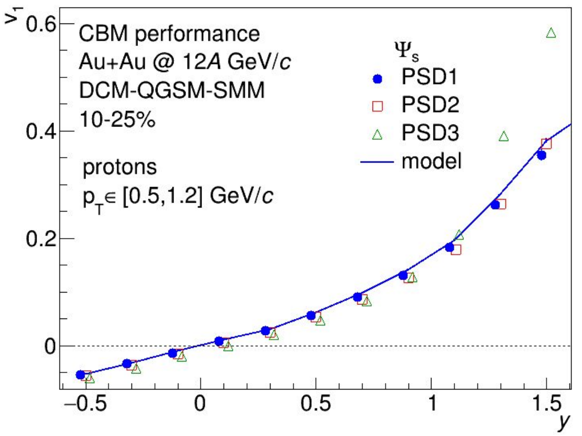
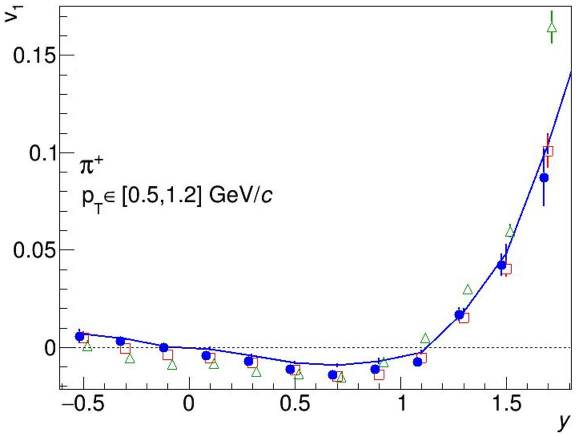
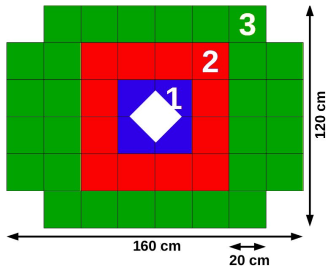
v_1 of protons, π^+ and K^+ vs. rapidity

Bayesian proton selection



Tracks matched to generator π^+





Results agree with the input v_1 for TOF-identified protons
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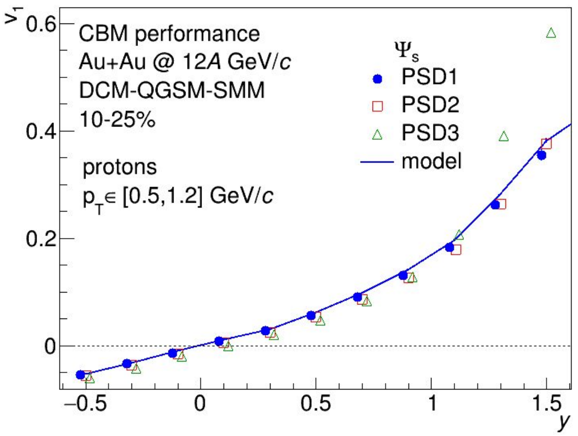
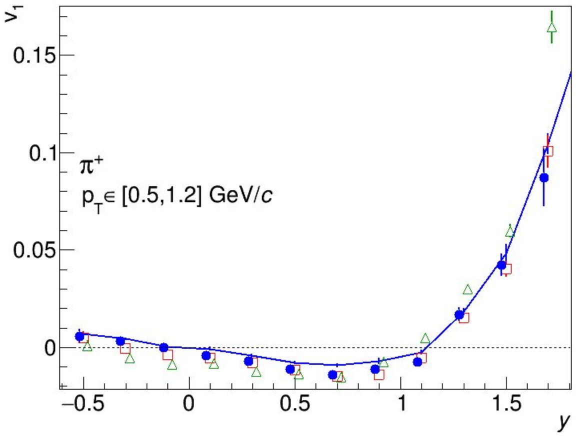
tracks matched to generator positive pions,

v_1 of protons, π^+ and K$^+$ vs. rapidity

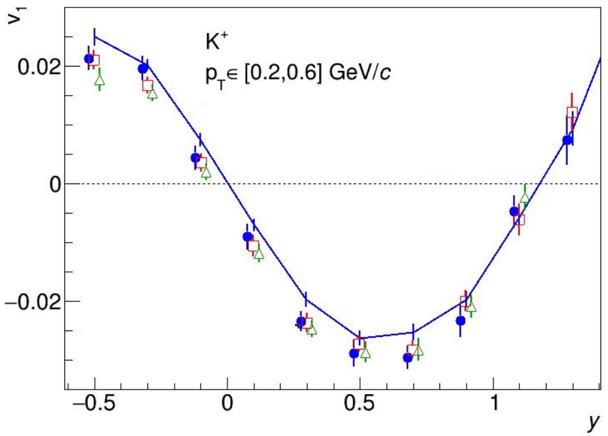
Bayesian proton selection

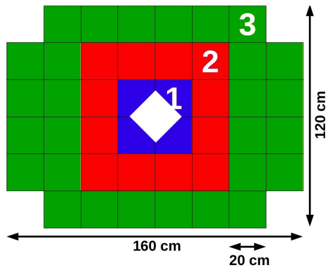


Tracks matched to generator π^+



Generator K$^+$





Results agree with the input v_1 for TOF-identified protons
(except for PSD3 due to non-flow),
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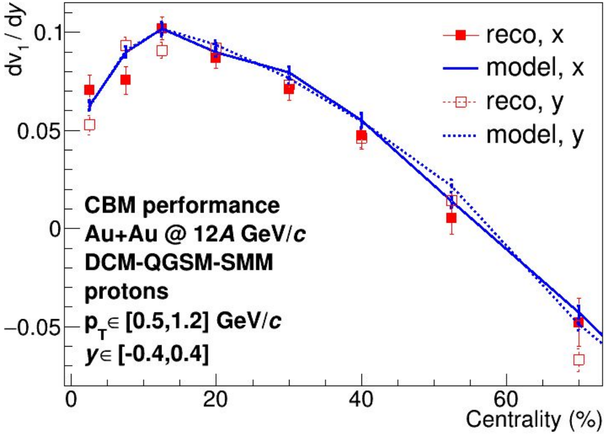
and generator K$^+$

Extraction of v_1 slope at midrapidity (dv_1/dy)

Bayesian proton selection

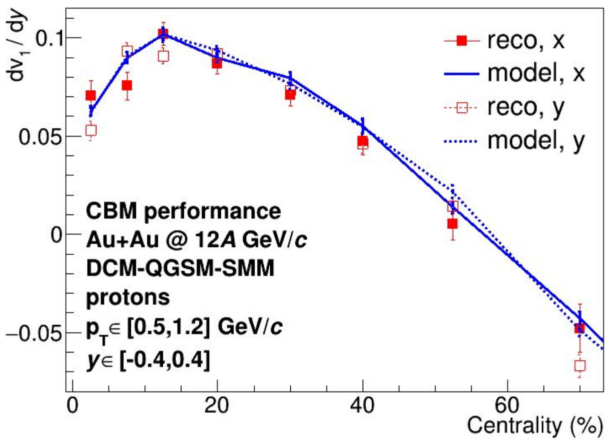


Protons: reliable extraction of dv_1/dy

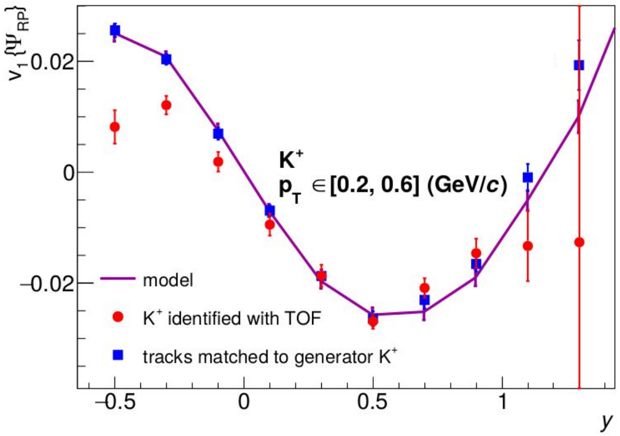
Central collisions require higher statistics

Extraction of v_1 slope at midrapidity (dv_1/dy)

Bayesian proton selection



K$^+$: Bayesian vs. MC-PID selection

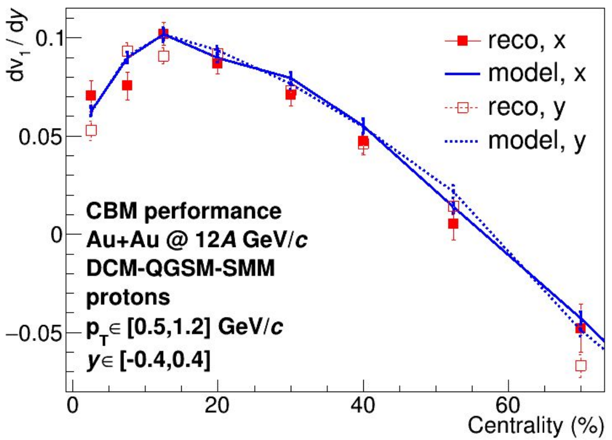


Protons: reliable extraction of dv_1/dy
Central collisions require higher statistics

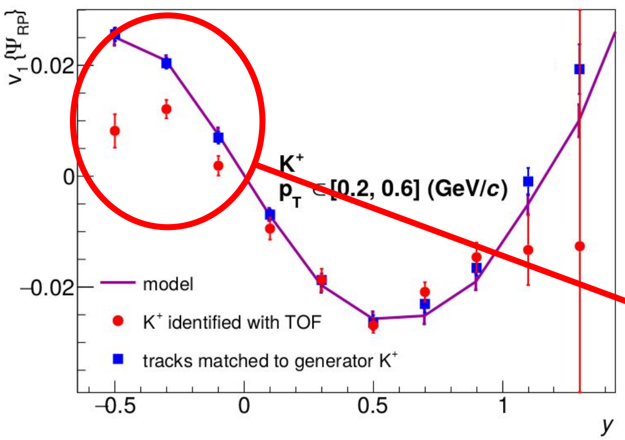
K$^+$: significant bias at backward rapidities
(important for dv_1/dy slope extraction)

Extraction of v_1 slope at midrapidity (dv_1/dy)

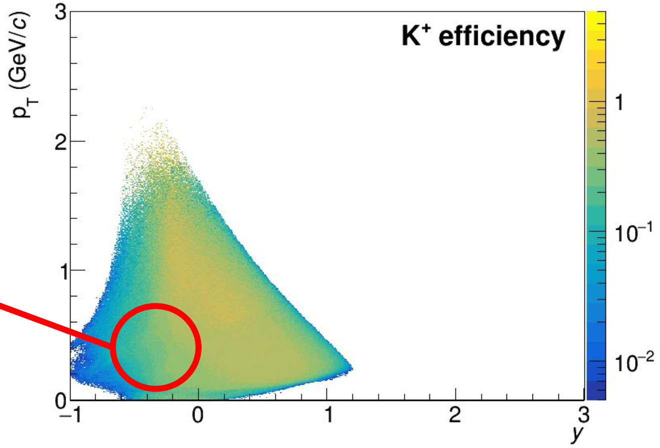
Bayesian proton selection



K^+ : Bayesian vs. MC-PID selection



K^+: efficiency



Protons: reliable extraction of dv_1/dy
Central collisions require higher statistics

K^+ : significant bias at backward rapidities
(important for dv_1/dy slope extraction)

- requires p_T-dependent efficiency correction
- investigate the purity of the Bayesian selection

Summary

- Anisotropic flow of hadrons allows to constrain the EoS of the QCD matter
  - Using data-driven methods, the CBM will be able to perform multi-differential measurements
- Presented CBM performance for protons, π^+, K^+ and proton v_1 as a function of p_T, y and centrality for Au+Au @ 12*A* GeV/*c* (SIS-100 energy scan is in preparation)
  - Investigated effects of the spectator plane estimation
  - Realistic centrality estimation using track multiplicity
  - Bayesian particle identification

Ongoing

- Implement (p_T, y)-dependent efficiency correction & estimate purity effects of the Bayesian identification
- Higher harmonics (elliptic flow v_2, et. al.)

Acknowledgement

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- the Ministry of Science and Higher Education of the Russian Federation, Project “Fundamental properties of elementary particles and cosmology” No 0723-2020-0041,
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- the European Union‘s Horizon 2020 research and innovation program under grant agreement No. 871072,
- the National Research Nuclear University MEPhI in the framework of the Russian Academic Excellence Project (contract no. 02.a03.21.0005, 27.08.2013).

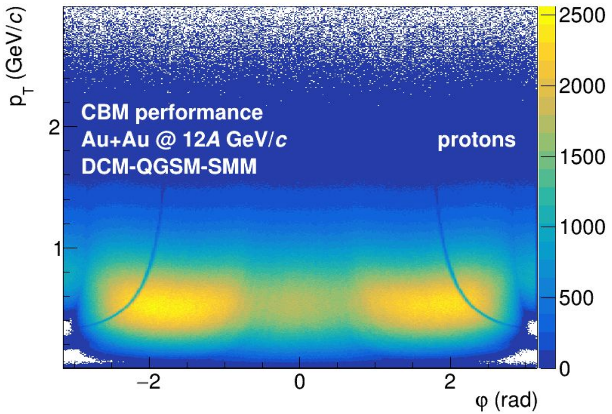
Backup

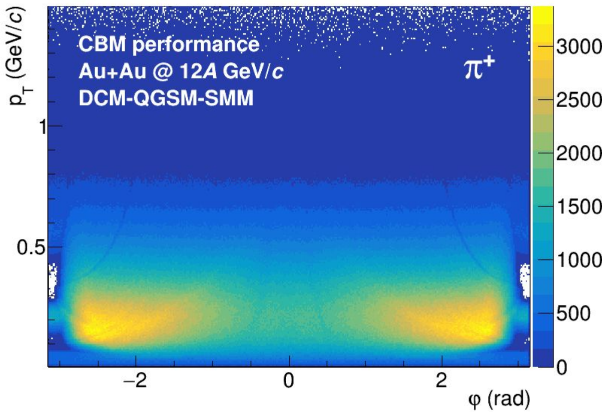
Azimuthal non-uniformity of the CBM response

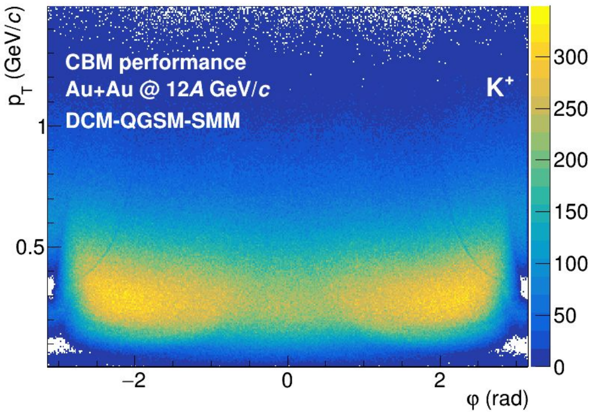
protons

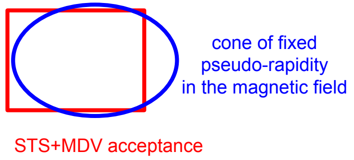
π^+

K^+



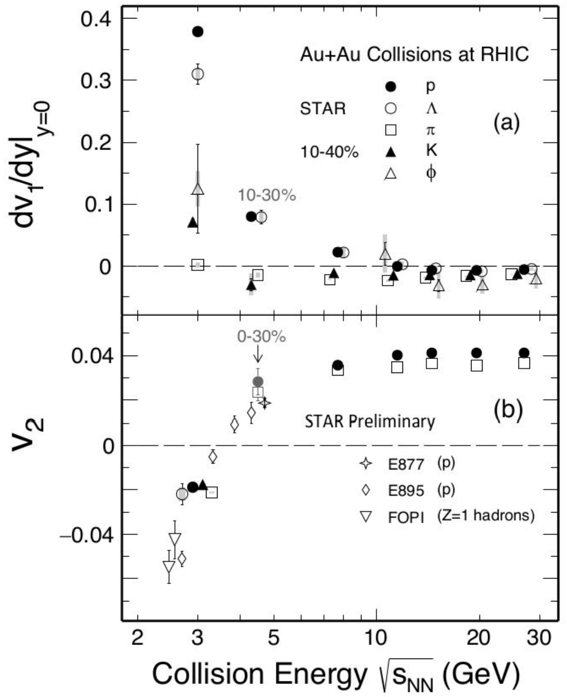




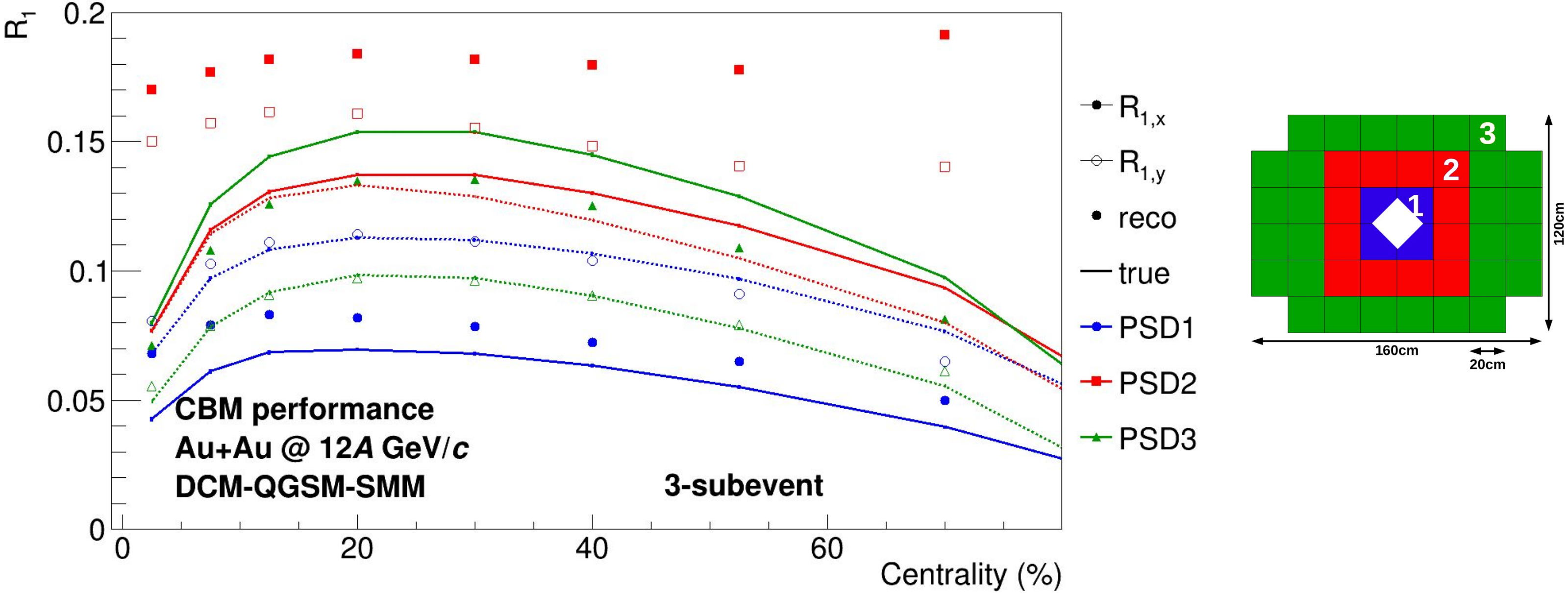


Azimuthal non-uniformity of the CBM detectors response:
(p_T, y)-differential corrections are needed!

New STAR preliminary from FXT program

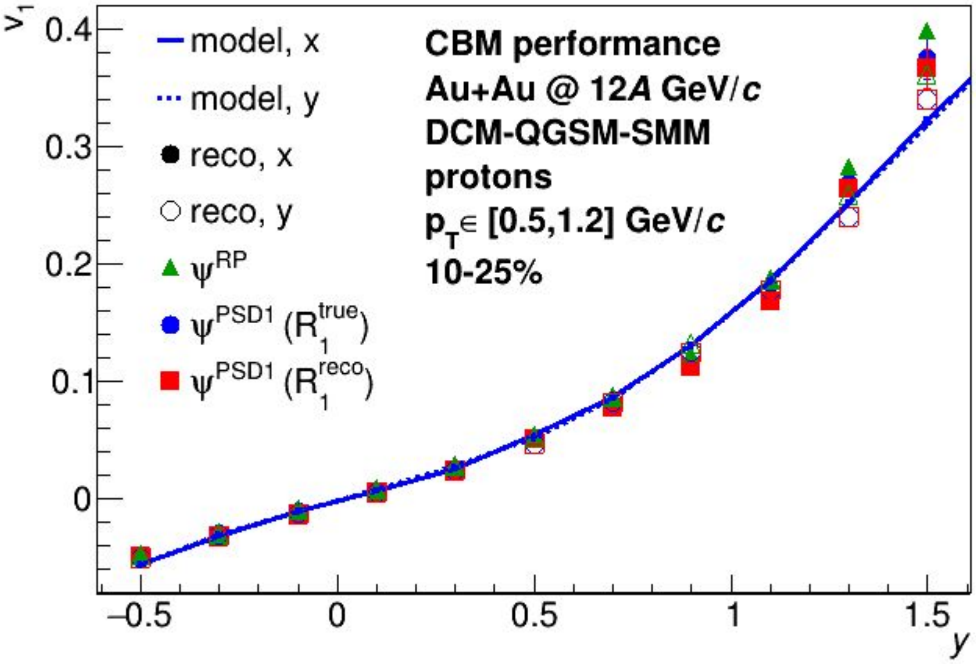


Resolution correction factor with 3-subevent method



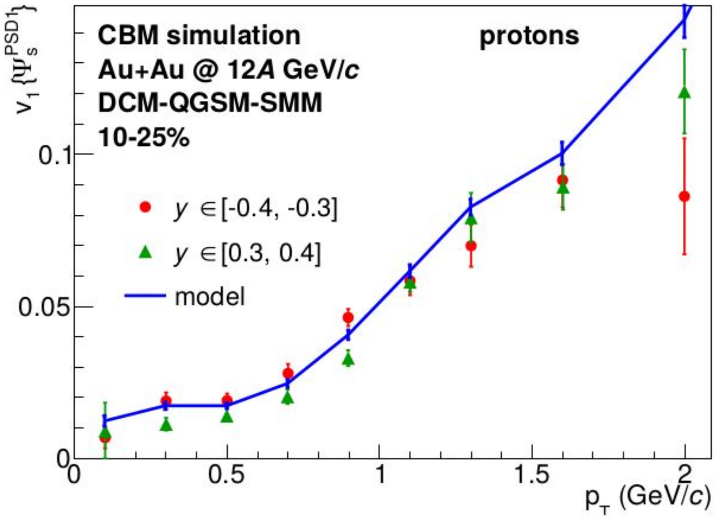
Significant bias in correlations due to hadronic shower leakage among the neighbouring PSD subevents

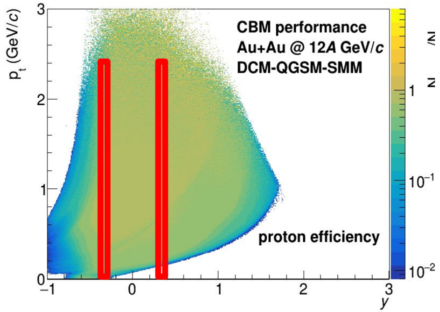
Proton v_1 vs. rapidity (PSD1 only)



Results for complete data driven analysis agrees with the input v_1

Proton v_1 vs. p_T for back/fwrd. rapidity windows





Better reconstruction efficiency at forward rapidity results in a more precise measurement