Performance study of the anisotropic flow and reaction plane reconstruction in the CBM experiment

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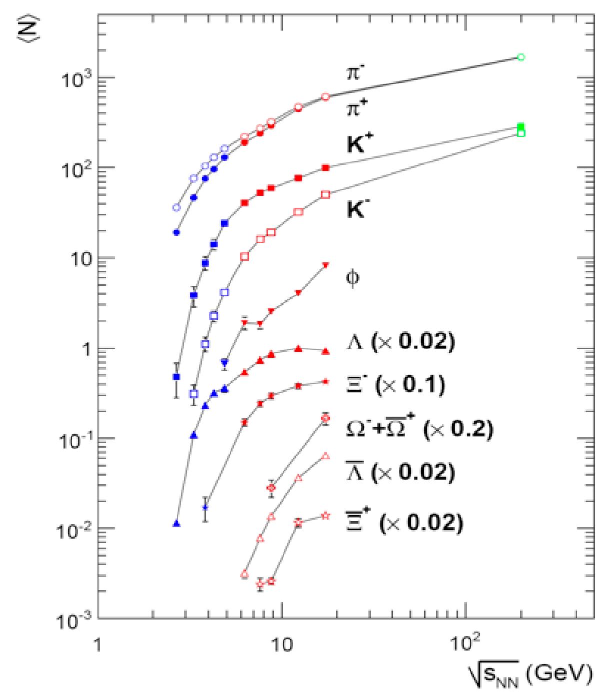
FAIRNESS 2016

14-19 February 2016, Garmisch-Partenkirchen

Motivation for particle flow measurements in heavy ion collisions at FAIR energies

- Collective flow of particles reflects the initial spatial anisotropy, sensitive to early stages of system evolution
- Directed flow (1st harmonic), elliptic flow (2nd harmonic): constraining the equation of state, access the region of phase diagram with high net-baryon density, relationship between pressure and volume for nuclear matter
- Higher orders: event-by-event fluctuations

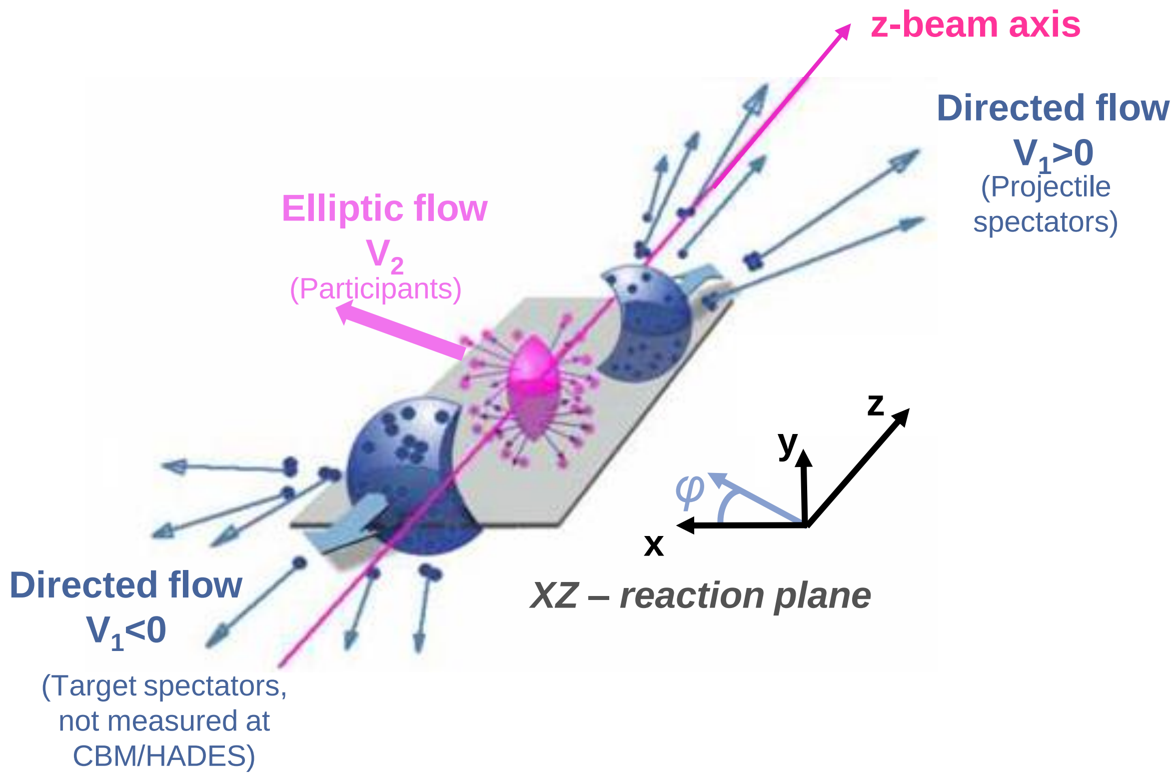
  - **SIS18/AGS: directed and elliptic flow was measured for protons, pions, kaons**
  - **HADES/CBM @ SIS100/300: extend flow measurement of light quark hadrons, measure the flow of rare particles, higher order flow harmonics**



Yield of mesons and hyperons vs. energy in central Au+Au or Pb+Pb collisions

Anisotropic flow in heavy ion collision

Collision of two heavy ions, eg. Au+Au, Pb+Pb, etc.

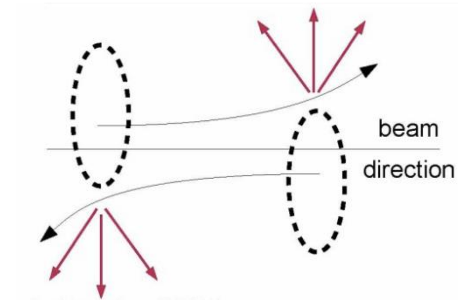


In non-central collisions flow of particles is usually described by Fourier decomposition with respect to reaction plane:

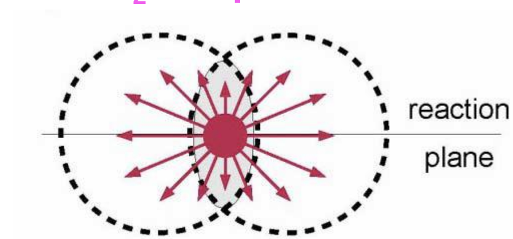
$$\frac{dN}{d(\Delta\phi)} \sim 1 + 2\sum_{n=1} v_n(p_t,\eta)\cos(n\Delta\phi)$$

$$\Delta\varphi = \varphi - \varphi_{RP}$$

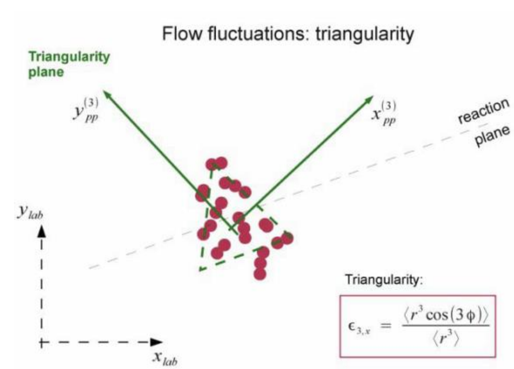
v_1 - directed flow



v_2 - elliptic flow



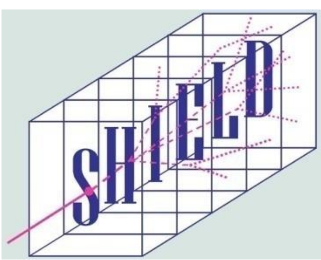
v_3 – triangular flow



Heavy-ion collision event generators

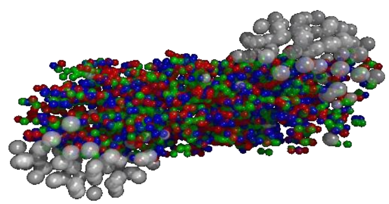
- For CBM performance study it is important to use a transport model consistent with the existing experimental data for flow.
- We investigate directed v_1, elliptic v_2 and higher orders flow harmonics in semicentral collisions in midrapidity region and extract from simulations the reaction plane resolution for different CBM subsystems.

Simulation: *Event generators + CBMROOT&GEANT4*



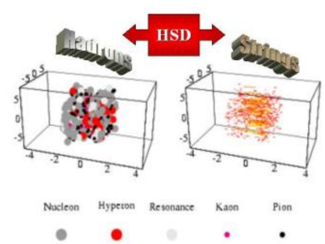
DCM-QGSM
& LA-QGSM

Spectators and their fragmentation



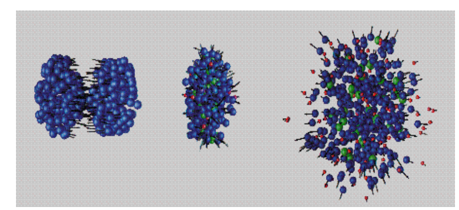
UrQMD v3.3

Most widely used



P/HSD v3.3

Parton / Hadron phases



iQMD

Strong flow, fragmentation, applicable up to 2 AGeV

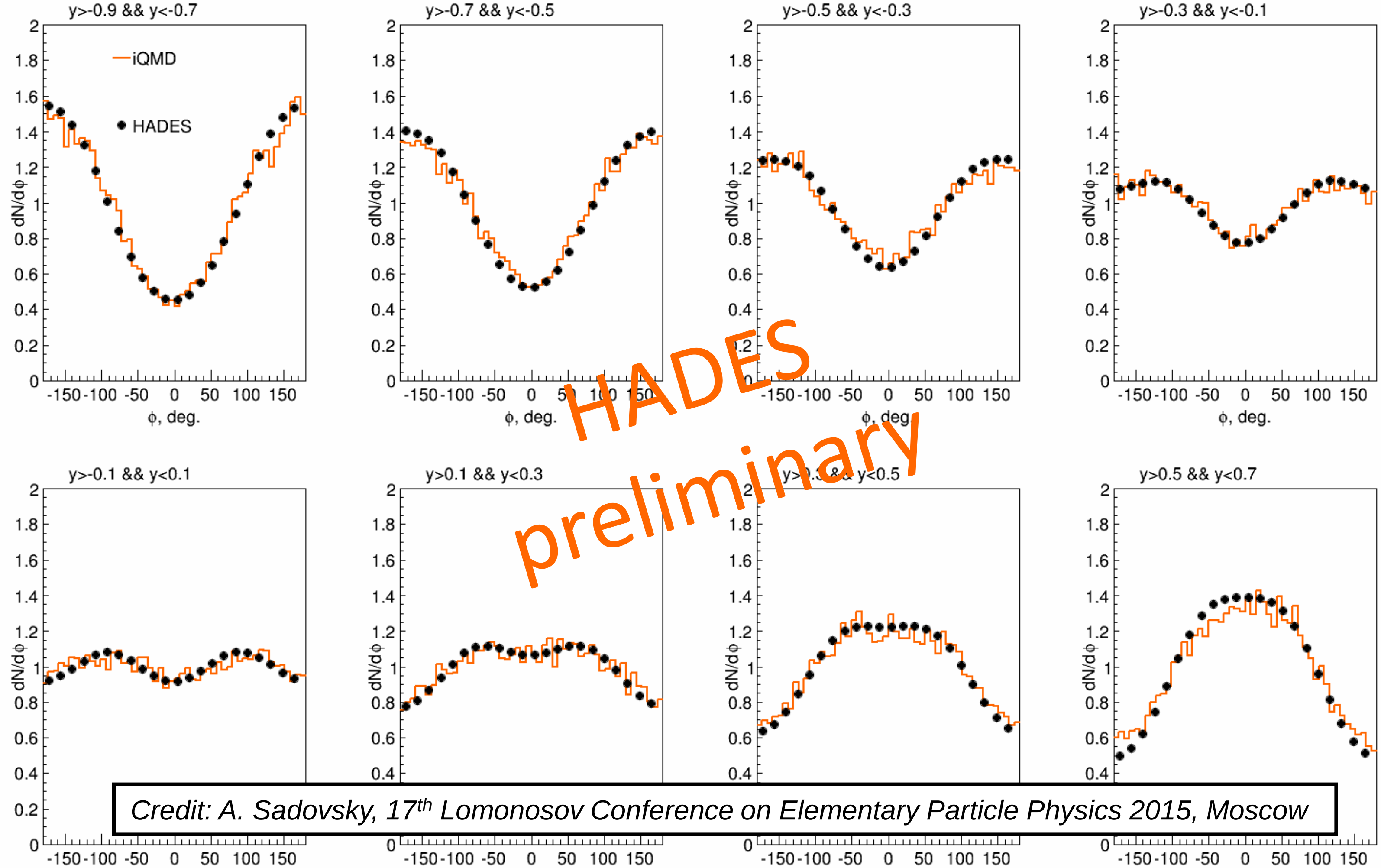
Simulated events & generators provided by Yvonne Leifels (iQMD), Volker Friese (UrQMD), Marina Golubeva (DCM-QGSM), Konstantin Gudima (LA-QGSM), Elena Bratkovskaya (P/HSD)

Proton flow at HADES@SIS18

Au+Au at 1.23 AGeV
semicentral collisions:
3.5fm<b<6.3fm & p_t>0.4

Proton azimuthal distributions wrt. to the reaction plane

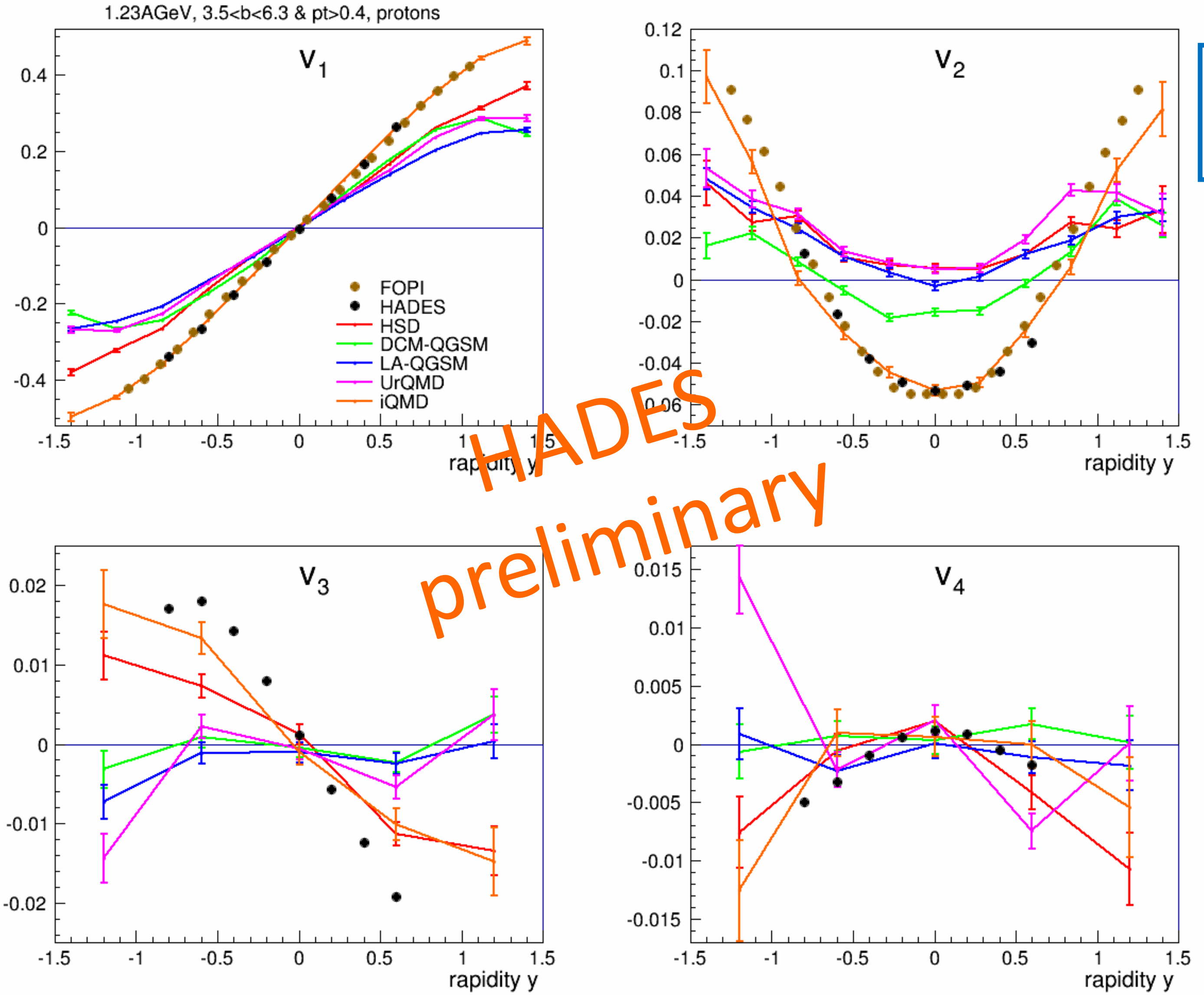
Azimuthal particle distributions in iQMD and HADES data agree well



Credit: A. Sadovsky, 17th Lomonosov Conference on Elementary Particle Physics 2015, Moscow

** $\varphi=\varphi-\varphi_{RP}$, for iQMD φ is smeared by detector resolution ≈ 35° (no detector simulation)*

Proton flow at HADES@SIS18

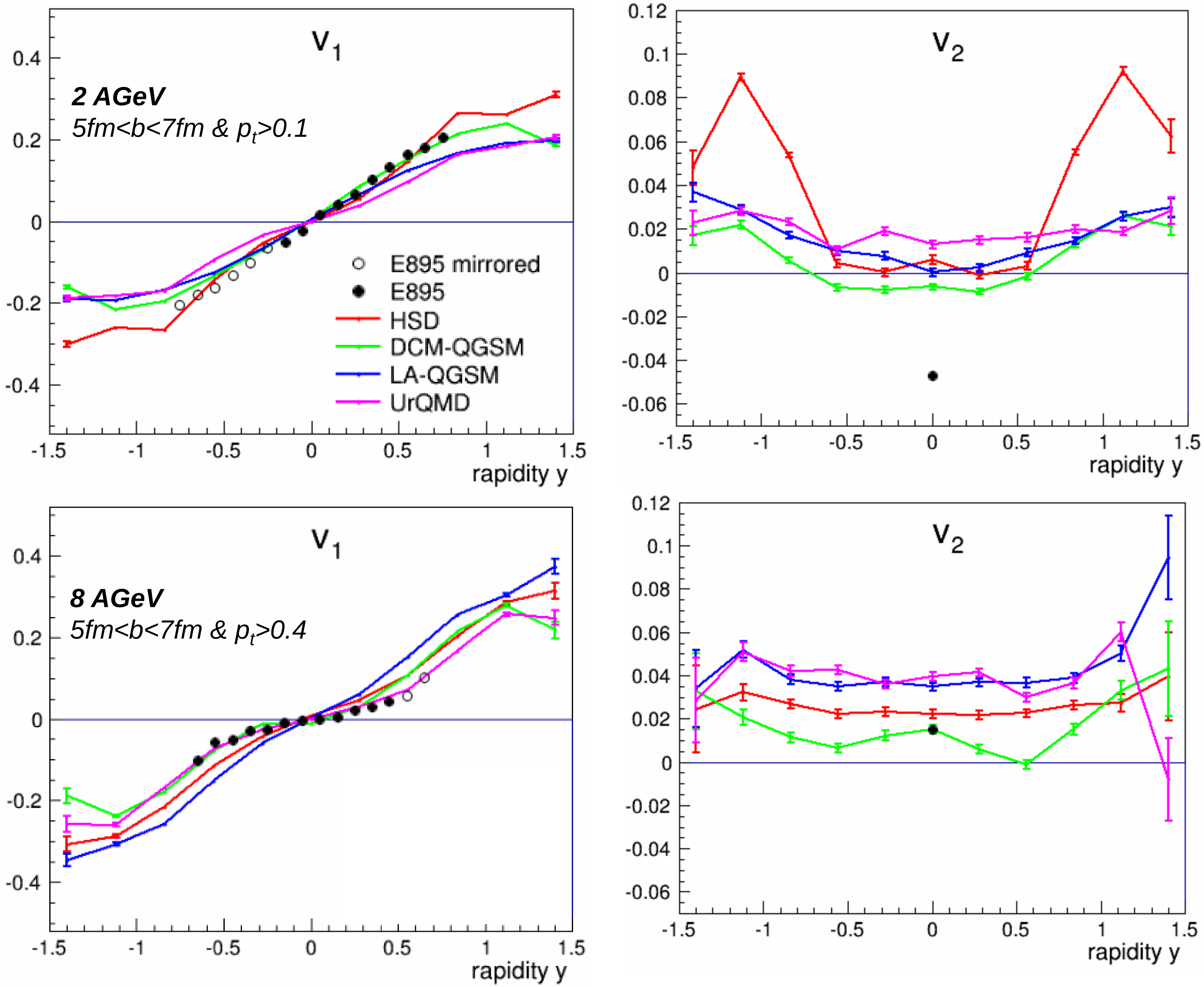


Au+Au at 1.23 AGeV
semicentral collisions:
3.5fm<b<6.3fm & p_t>0.4

- v_1 & v_2 in iQMD agree with FOPI and HADES data
- other models do not describe data below 2 AGeV well
- non-zero triangular v_3 component described by IQMD & HSD

Credit: A. Sadovsky, 17th Lomonosov Conference on Elementary Particle Physics 2015, Moscow

Proton flow at CBM@SIS100



Au+Au *semicentral collisions*

- *v_1 is described best by DCM-QGSM in a whole energy range*
- *v_2 is described best by DCM-QGSM at 4-8 AGeV*

Energy dependence of the proton directed v_1 flow slope at midrapidity

$\frac{dv_1}{dy}$ *at midrapidity -0.5<y<0.5*

with cuts:

1.23AGeV: pt>0.4, 3.5<b<6.3

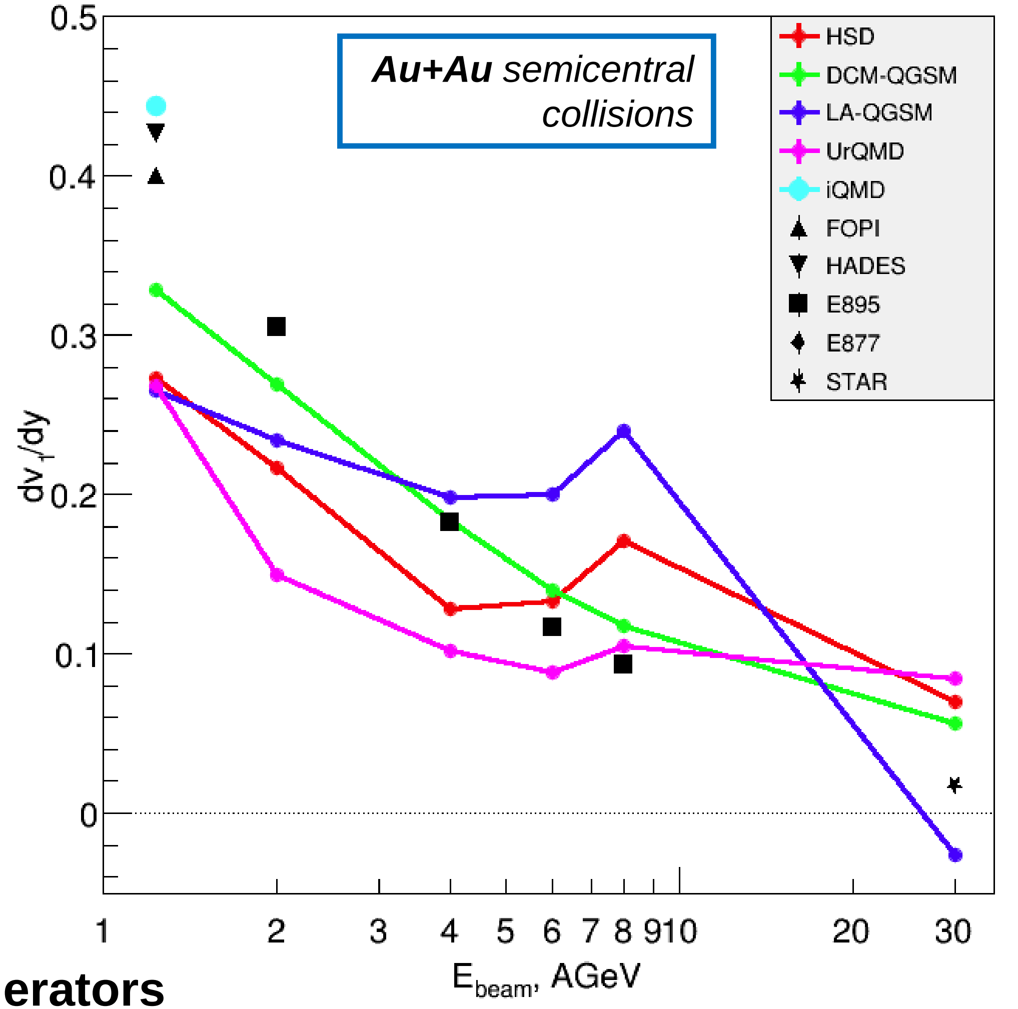
2-4AGeV: pt>0.1, 5<b<7

6AGeV: pt>0.2, 5<b<7

8AGeV: pt>0.4, 5<b<7

30AGeV: pt>0.2, 4.5<b<9.2

- Flow “jump” at 8 AGeV at all generators except for DCM-QGSM.
- iQMD is the closest to data at 1.23 AGeV
- Some discrepancy with data at 30 AGeV for all models



Directed flow varies for different generators

DCM-QGSM is overall the most consistent with data

Energy dependence of the proton elliptic v_2 flow at midrapidity

v_2 at midrapidity y=0

with cuts:

1.23AGeV: pt>0.4, 3.5<b<6.3

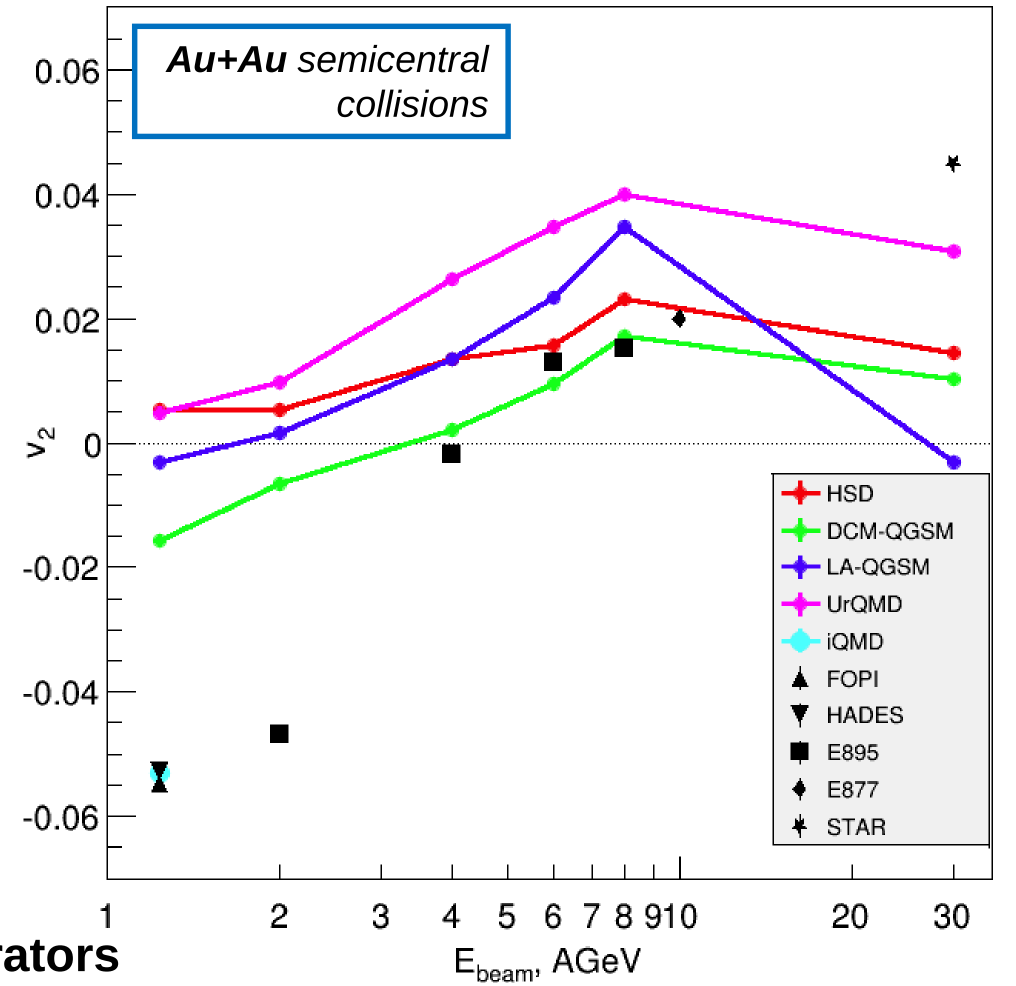
2-4AGeV: pt>0.1, 5<b<7

6AGeV: pt>0.2, 5<b<7

8AGeV: pt>0.4, 5<b<7

30AGeV: pt>0.2, 4.5<b<9.2

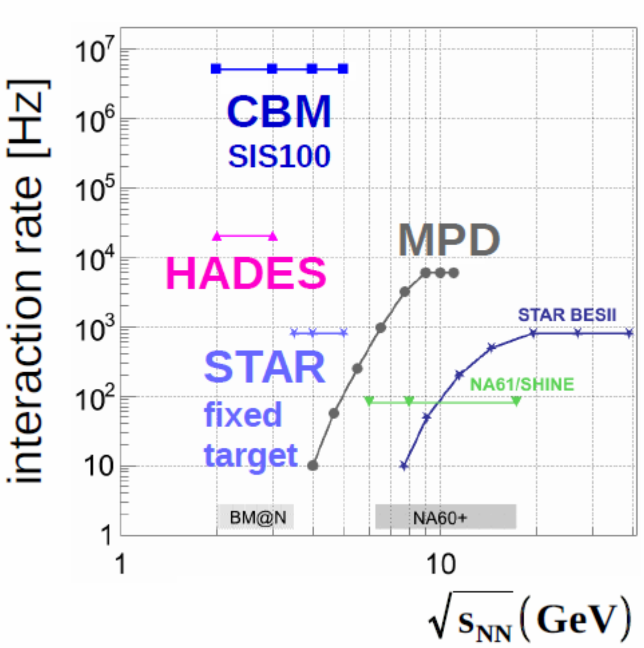
- Only iQMD agrees with data at 1.23 AGeV
- DCM-QGSM agrees with data at 4-8 AGeV
- High discrepancy with data at 2 and 30 AGeV for all models



Elliptic flow varies for different generators

iQMD agrees with data at 1.23 AGeV, DCM-QGSM agrees with data at 4-8 AGeV

CBM physics program and requirements



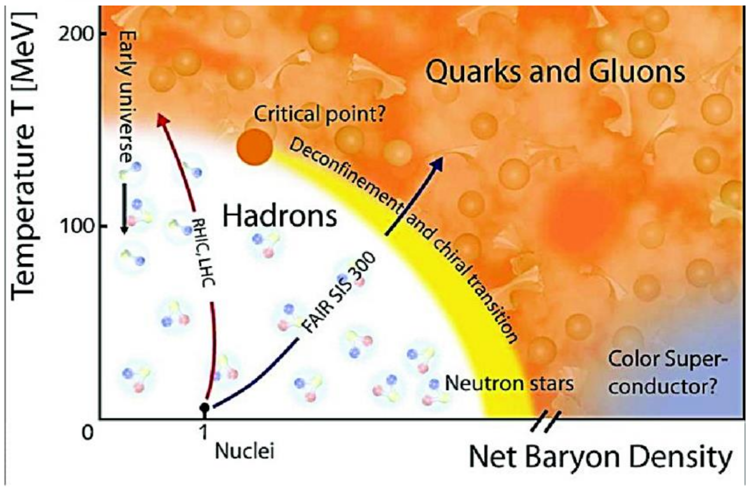
Detector requirements:

- High statistics via high event rates

10^5 - 10^7 Au+Au reactions/sec:

  - Radiation hard detectors
  - High speed data acquisition

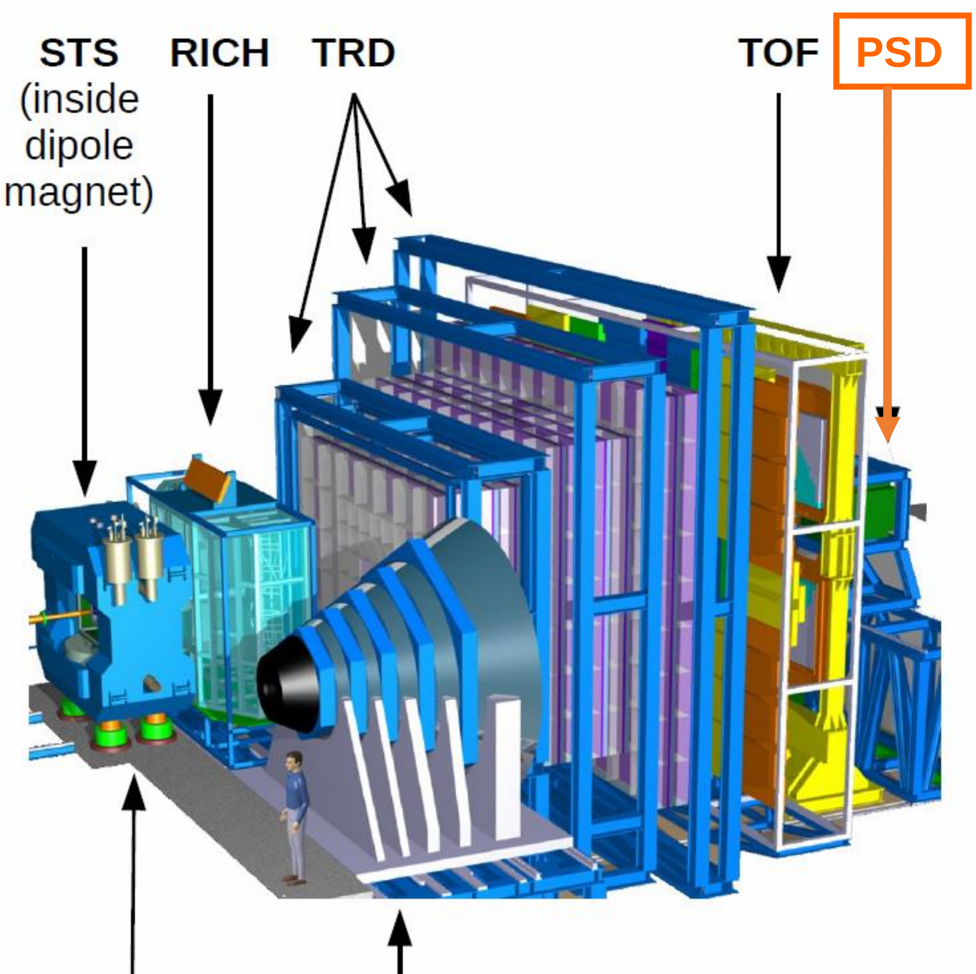
- Particle identification: hadrons and leptons, charm measurements



Detector observables:

- Nuclear matter equation-of-state at large baryon densities, coexistence (quarkyonic) & partonic phases
- Chiral symmetry at large baryon densities
- Charm production and propagation at threshold energies
- Strange nuclear matter

CBM detector overview



Dipole Magnet
bends particle's trajectories
for momentum measurement

STS (Silicon Tracking System)
charged particle tracking

RICH (Ring Imaging CHerenkov)
TRD (Transition Radiation Detector)
electron identification

TOF (Time of Flight detector)
hadron identification

PSD (Projectile Spectator Detector)
collision centrality and
reaction plane determination

MVD (Micro-Vertex Detector)
secondary vertex reconstruction

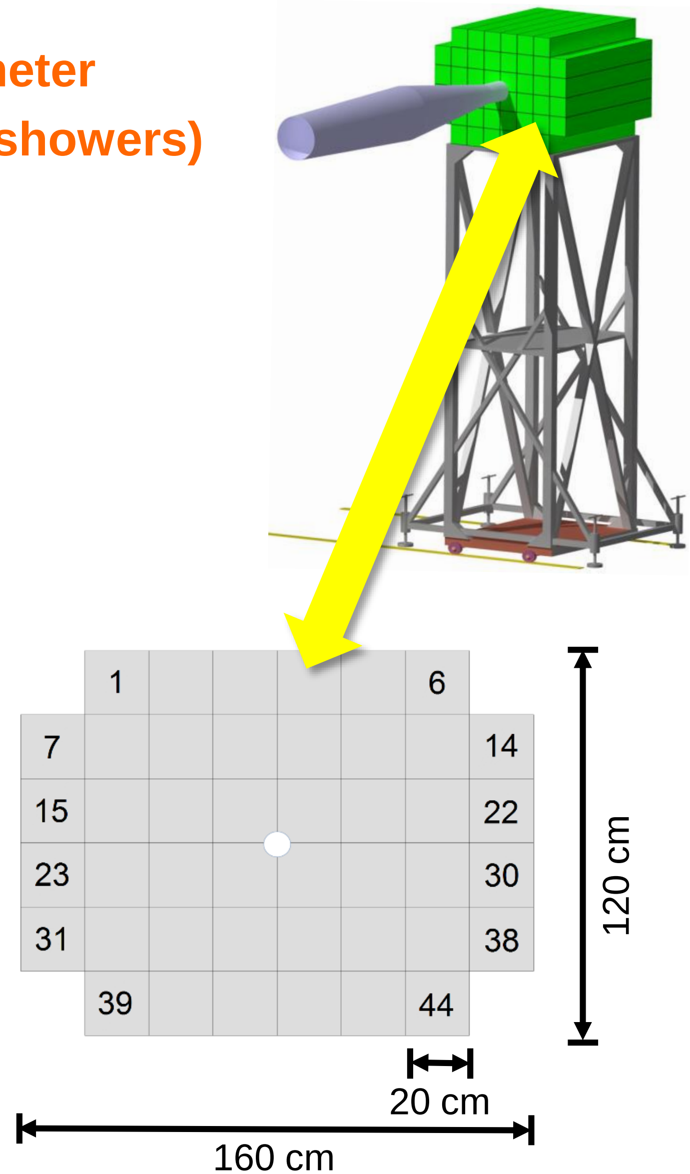
MUCH (MUon CHambers)
muon identification

DAQ/FLES (First-level Event Selector)
online reconstruction / event selection,
High Performance Computing

CBM Projectile Spectator Detector

PSD is a compensating lead-scintillator calorimeter (measures both hadronic and electromagnetic showers)

PSD task is to measure energy distribution of projectile nuclei fragments (spectators) and forward going particles produced close to the beam rapidity *

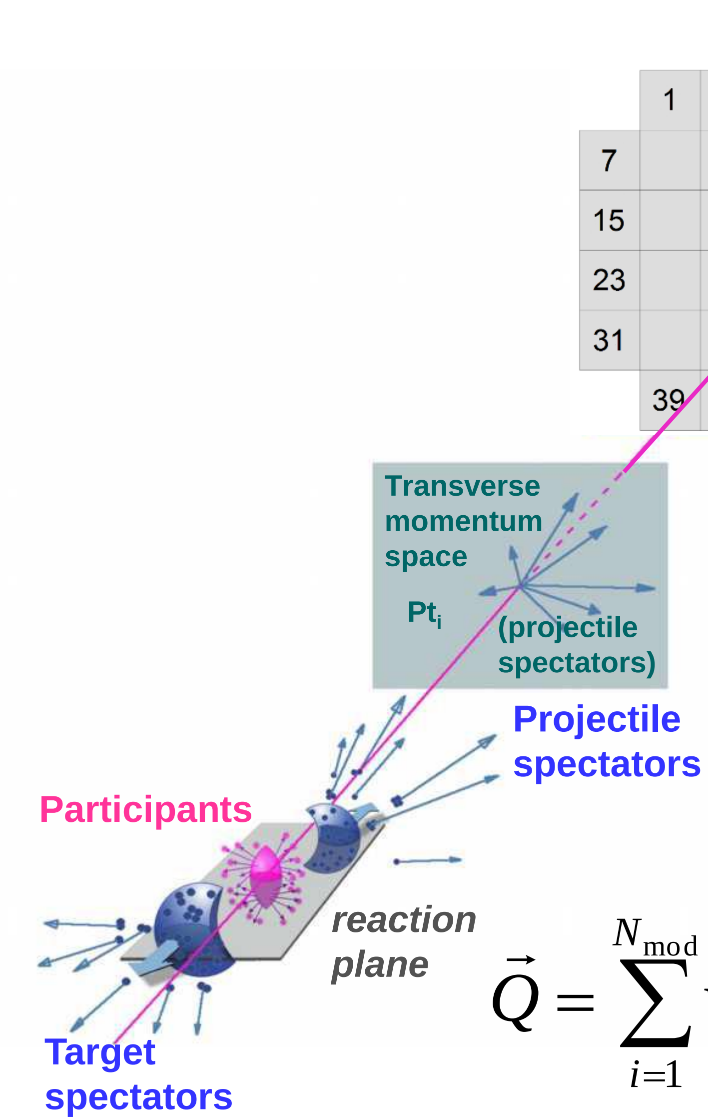


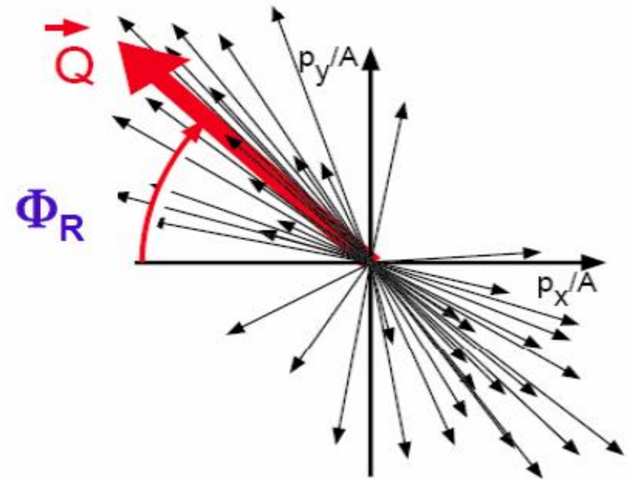
Event-by-event determination of the initial event geometry:

- Use spectators deflection to determine the reaction plane
→ required for anisotropic flow studies in CBM
- Use spectator multiplicity (energy) to determine collision centrality

** Technical Design Report for the CBM PSD*

Reaction plane reconstruction





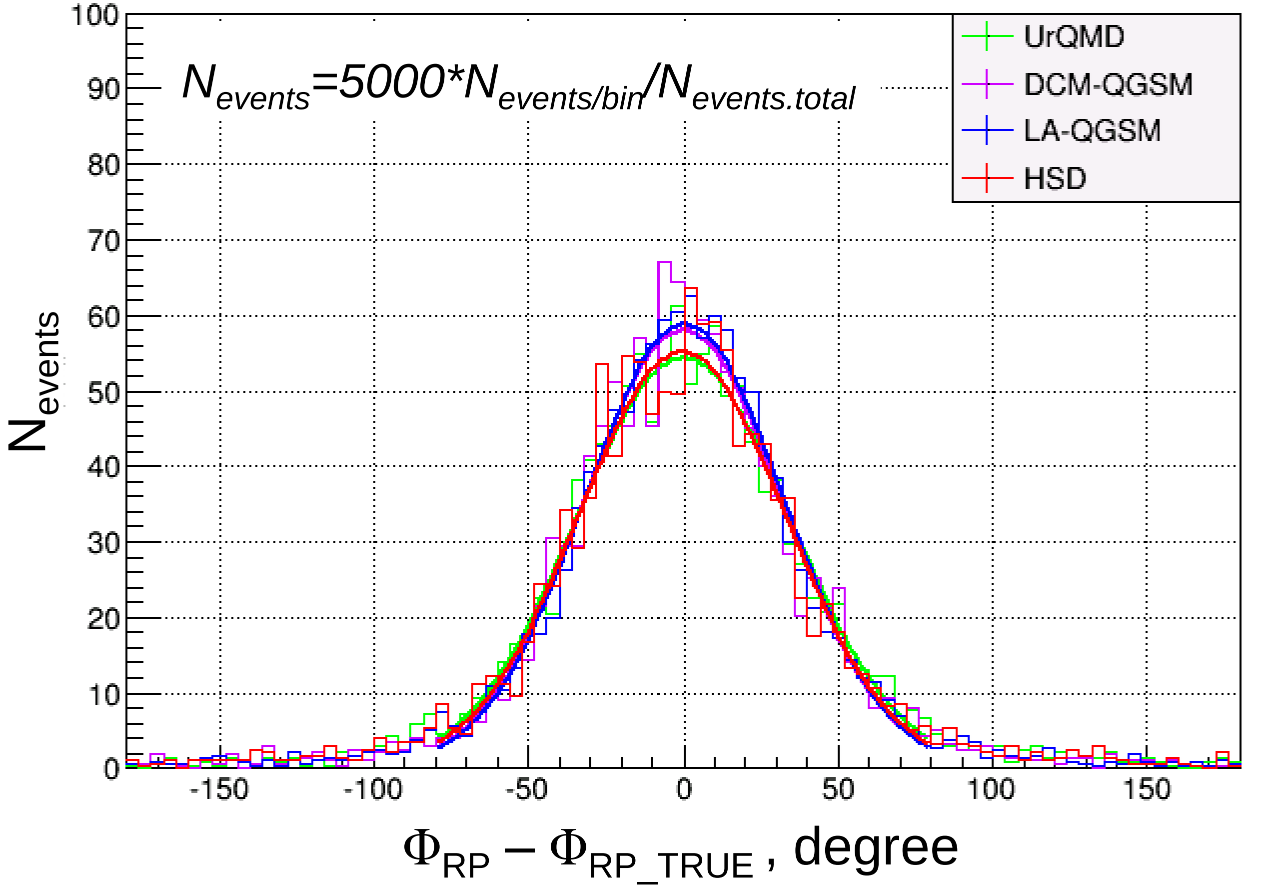
$$\Phi_R = a\cos\left(\sum_{i=1}^{N_{sp}} \frac{p_x}{p_t}\right) \qquad \vec{Q} = \sum_{i=1}^{N_{sp}} w_i \frac{\vec{p}_t^{\,i}}{\left|\vec{p}_t^{\,i}\right|}$$

$$\vec{Q} = \sum_{i=1}^{N_{\mathrm{mod}}} w_i \frac{\vec{r}_i}{\left|\vec{r}_i\right|}$$

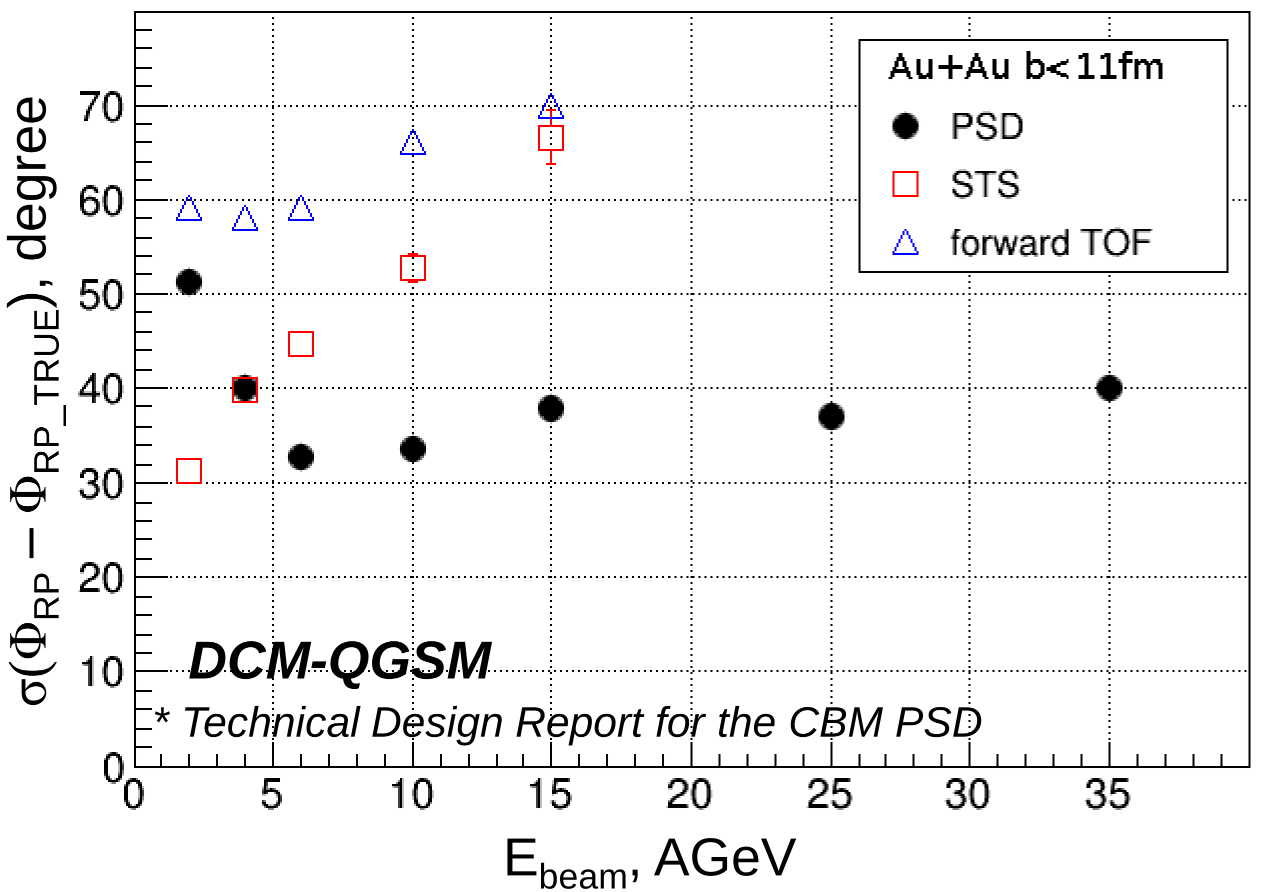
$\vec{Q}$ – *flow vector;*
N_{mod} – *number of PSD modules (44);*
w_i – *weight factor: w_i>0 for projectile, w_i<0 for target,*
$|w_i|$ = *energy deposited in i-module;*
$\vec{r}_i$ – *position vector of i-module.*

PSD reaction plane resolution: $\varphi_{RP\_reco} - \varphi_{RP\_true}$

***8 AGeV Au+Au** semicentral collisions: 5fm<b<10fm*

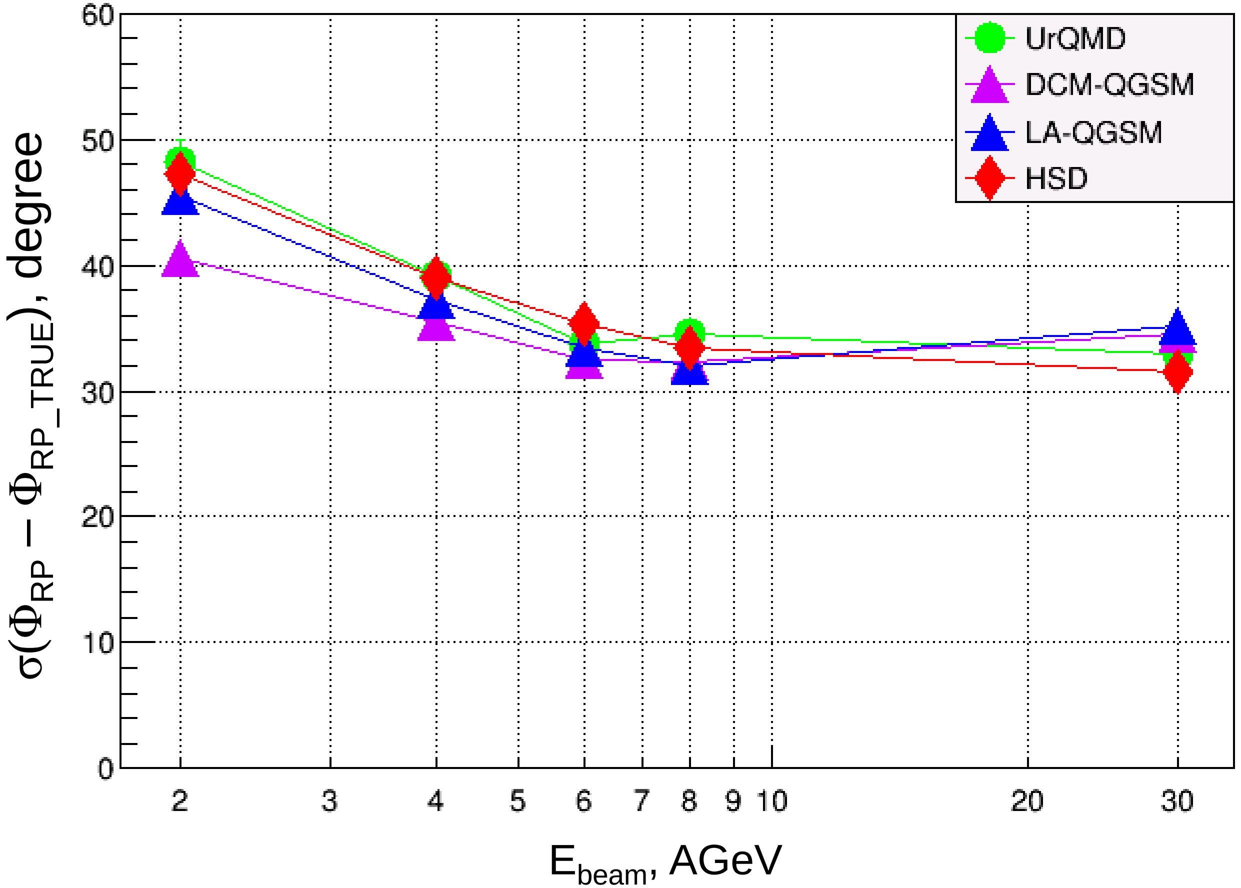


Reaction plane resolution: PSD vs. STS vs. f. TOF



PSD shows the best resolution at energies higher than 4 AGeV, for lower energies STS performs better

Reaction plane resolution: different event generators



***Au+Au** semicentral collisions: 5fm<b<10fm*

Simple PSD geometry: Cave + Pipe + Target + STS + PSD with magnetic field

Resolutions below 35 degrees at E>=4 AGeV, consistent with previous results

Reaction plane resolution does not differ much for different generators

SUMMARY & OUTLOOK

- Anisotropic flow is an excellent observable to study the evolution of a heavy-ion collisions (equation of state, properties of the dense nuclear matter).
- CBM plans to measure the flow of light hadrons and rare probes (kaons, hyperons,etc) with very high precision.
- The precise determination of the collision reaction plane is required for the precision flow measurements within CBM.

- ✓ Five heavy-ion collision event generators: iQMD, UrQMD, DCM-QGSM, LA-QGSM and HSD were used to compare v_1-v_4 flow with FOPI, HADES, AGS E895 & E877, and STAR experimental data.
- ✓ PSD allows for the reaction plane determination with spectators.
- ✓ PSD combined with STS works well for the precise reaction plane determination.

Thank you for attention!

Nuclear Research Institute AS CR, Řež

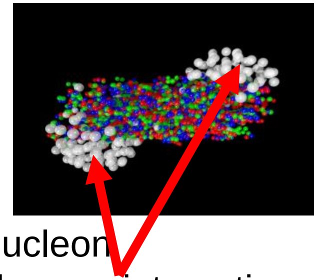
Backup:
CBM PSD Performance

(from talk of I. Selyuzhenkov at DPG2015)

Centrality determination

Number of interacting participants:

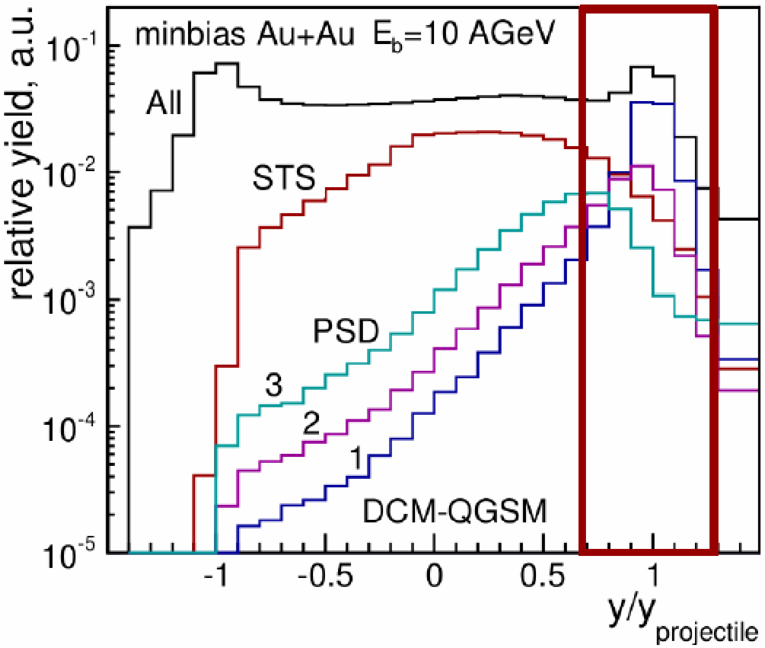
$$N_p = A - \frac{E_s}{E_a}$$



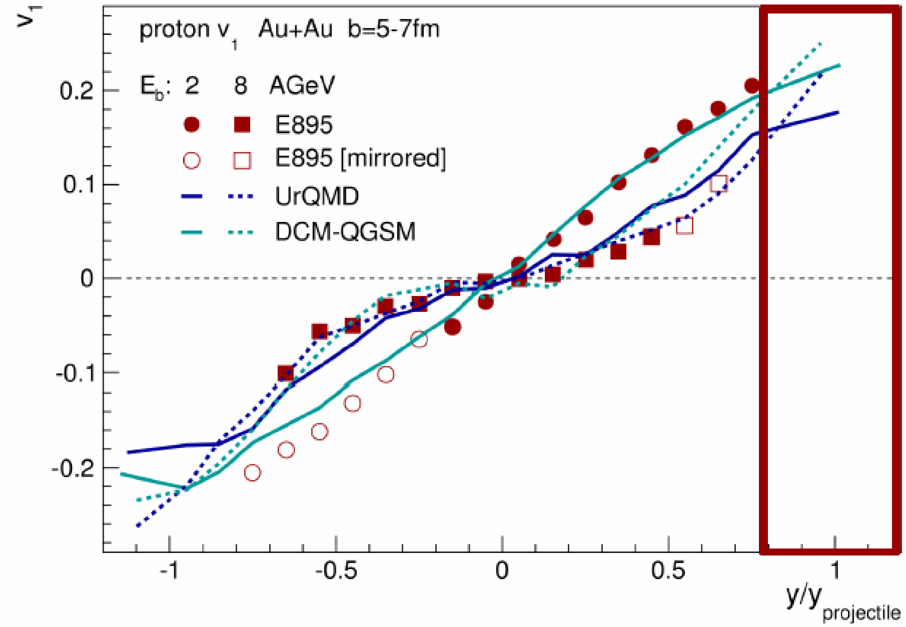
A – mass number of ion
E_a – beam energy per nucleon
E_s – energy carried by the non-interacting nucleons (projectile spectators) -
- measured by Hadron Calorimeter

Why spectators are relevant for event geometry determination in CBM?

yields of participants & spectators



directed (v_1) flow

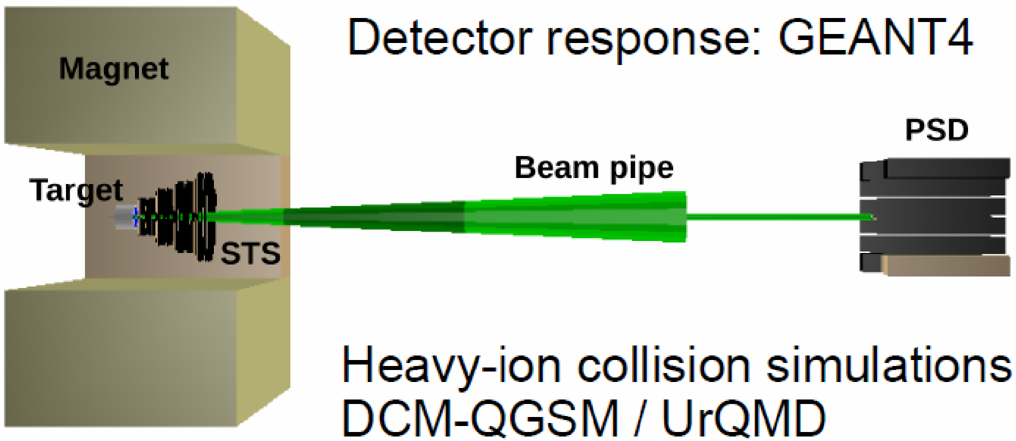


Forward (spectator) region is well suited for collision geometry determination:

- Provide an independent method to determine centrality
  → important to validate the "participant" centrality estimates at midrapidity
- Strong v_1 (compared to weak v_1 seen by midrapidity detectors of CBM)
  → better reaction plane resolution

Simulation setup for physics performance study

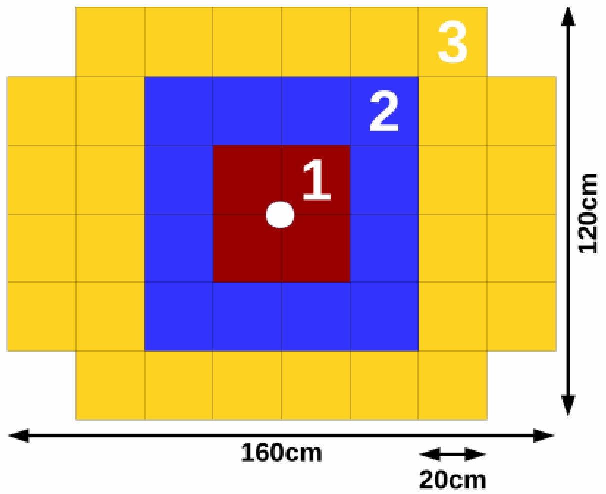
Simulation setup



Detector response: GEANT4

Heavy-ion collision simulations:
DCM-QGSM / UrQMD

Transverse geometry



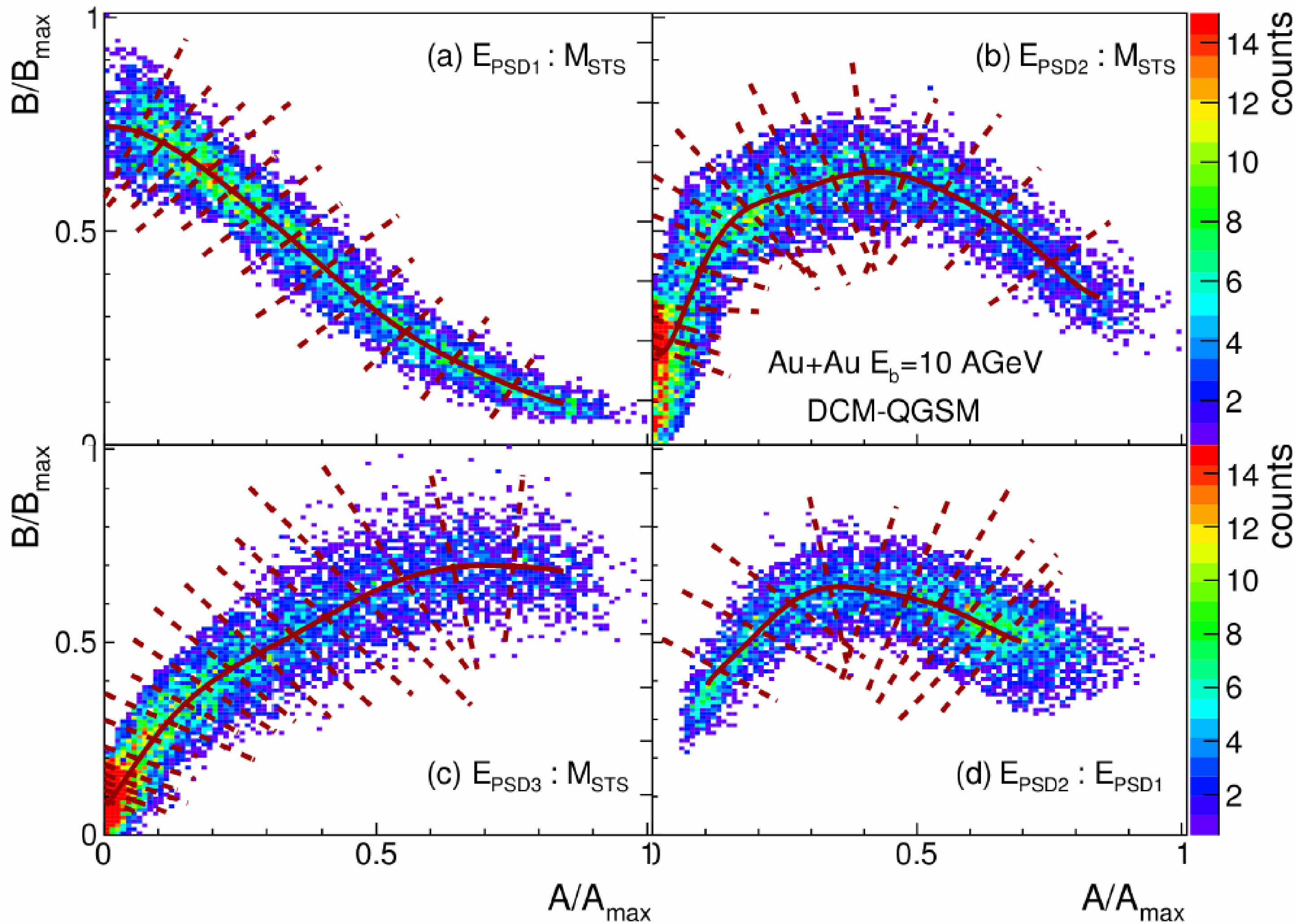
Elongated geometry accounts for smearing of charge fragment distribution along the x-axis by the CBM Magnet:

- Important for azimuthal asymmetry measurements such as anisotropic flow / reaction plane reconstruction

Using subevents:

- allows to use the PSD detector standalone for both centrality and event plane resolution determination
- in a combination with an STS tracking sub-detector helps to improve the overall centrality resolution in CBM

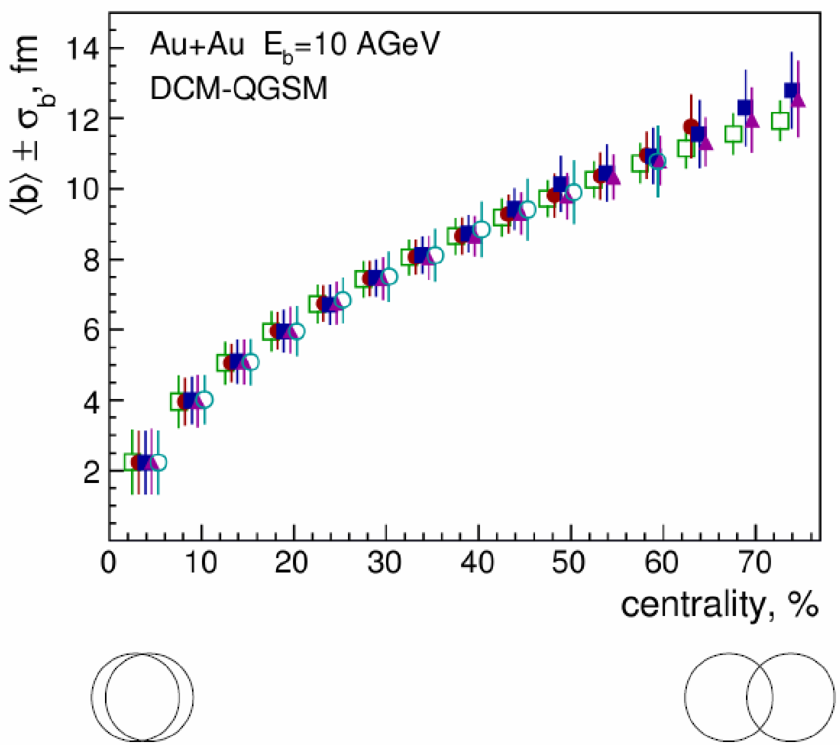
Centrality determination in CBM: Correlation between PSD subevents & STS track multiplicity



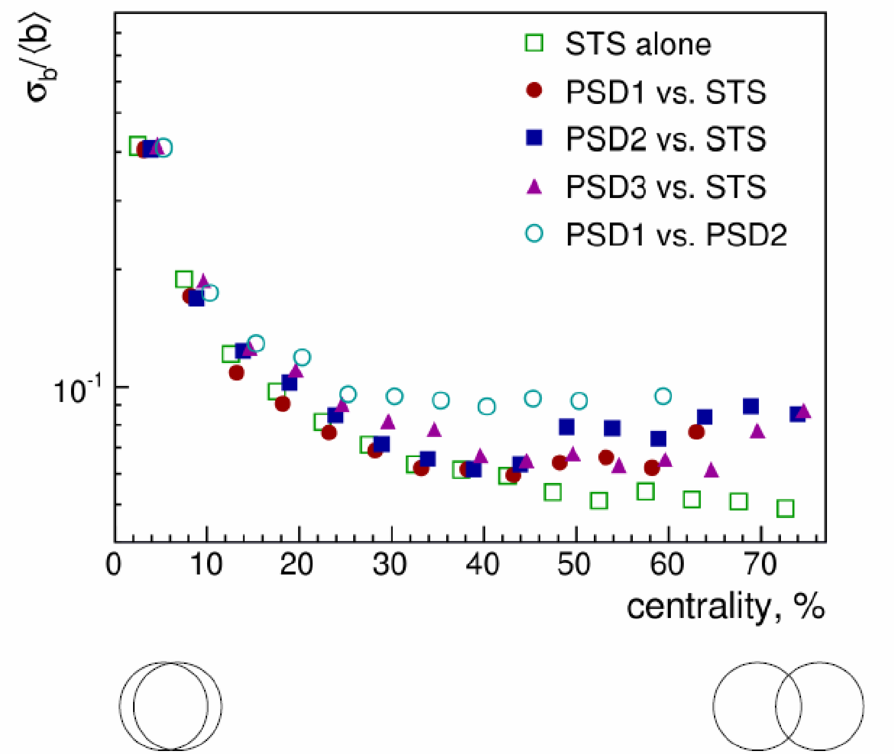
Two (mutli)-dimentional correlations of energy deposited in PSD subevents can be used to define centrality classes

Centrality determination

Average impact parameter, b



relative width (~centrality resolution)



- PSD can be used standalone as an independent centrality estimator with a resolution for centrality of 10%
- PSD helps to improve resolution of the STS for (mid-)central collisions

Anisotropic flow measurement techniques

$$\frac{dN}{d(\varphi_i - \Psi_n)} \sim 1 + 2 \sum_{n=1} v_n \cos[n(\varphi_i - \Psi_n)]$$

$$v_n = \langle \cos[n(\varphi_i - \Psi_n)] \rangle$$

- directly calculable only in theory when the collision symmetry plane orientation is known

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Experimental estimate of the collision symmetry plane based on the measured azimuthal distribution of particles (event plane angle):

$$\Psi_n \rightarrow \Psi_{n,EP} \quad \longrightarrow \quad v_n\{EP\} = \frac{\langle \cos[n(\varphi_i - \Psi_{EP}^n)] \rangle}{R_n}$$

R_n - event plane resolution correction factor

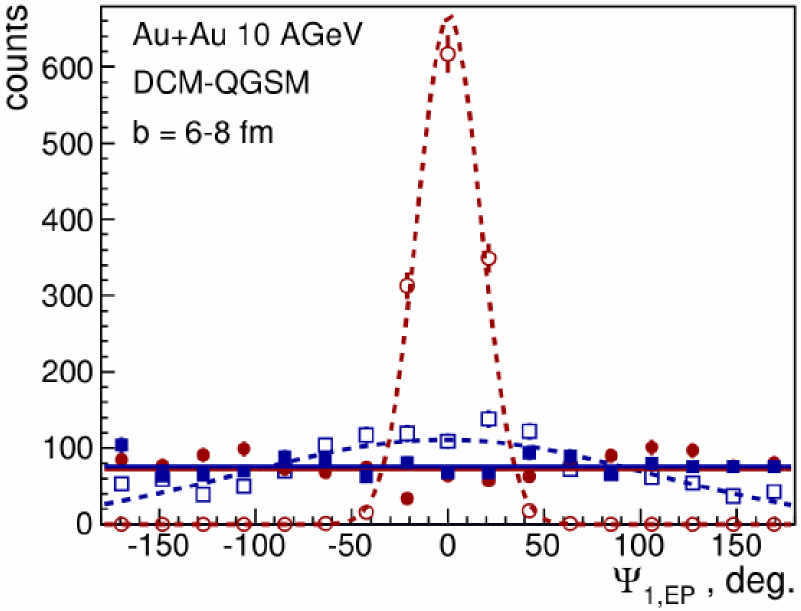
Using PSD, the event plane angle is defined by center of gravity shift of spectator transverse energy distribution deposited in the PSD (Q- vector):

$$Q = (Q_x, Q_y) = \sum_i w_i (\cos\varphi_i, \sin\varphi_i) \qquad \Psi_{1,EP} = atan2(Q_y, Q_x)$$

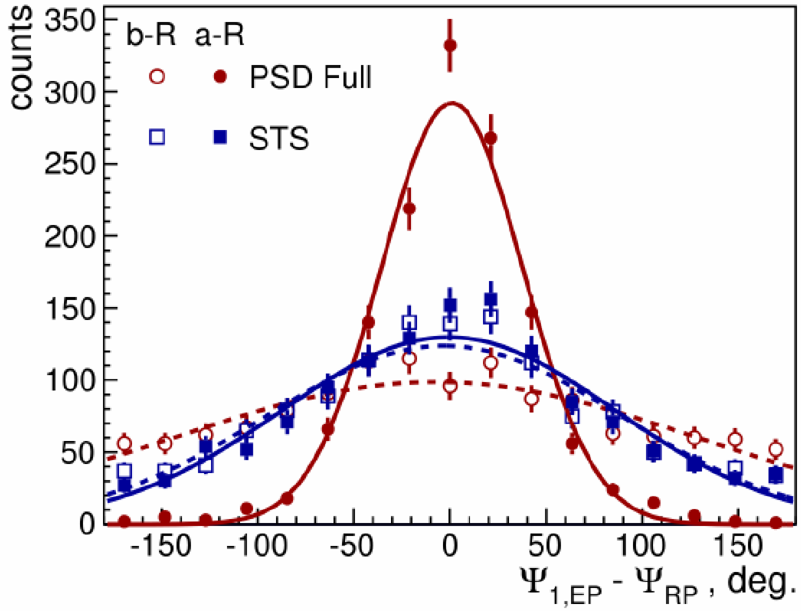
Detector corrections for azimuthal non-uniformity

Q-vector recentering: $$Q_{x,y} = \frac{Q_{x,y} - \langle Q_{x,y} \rangle}{\langle Q_{x,y} \rangle}$$

Event plane distribution before and after recentering



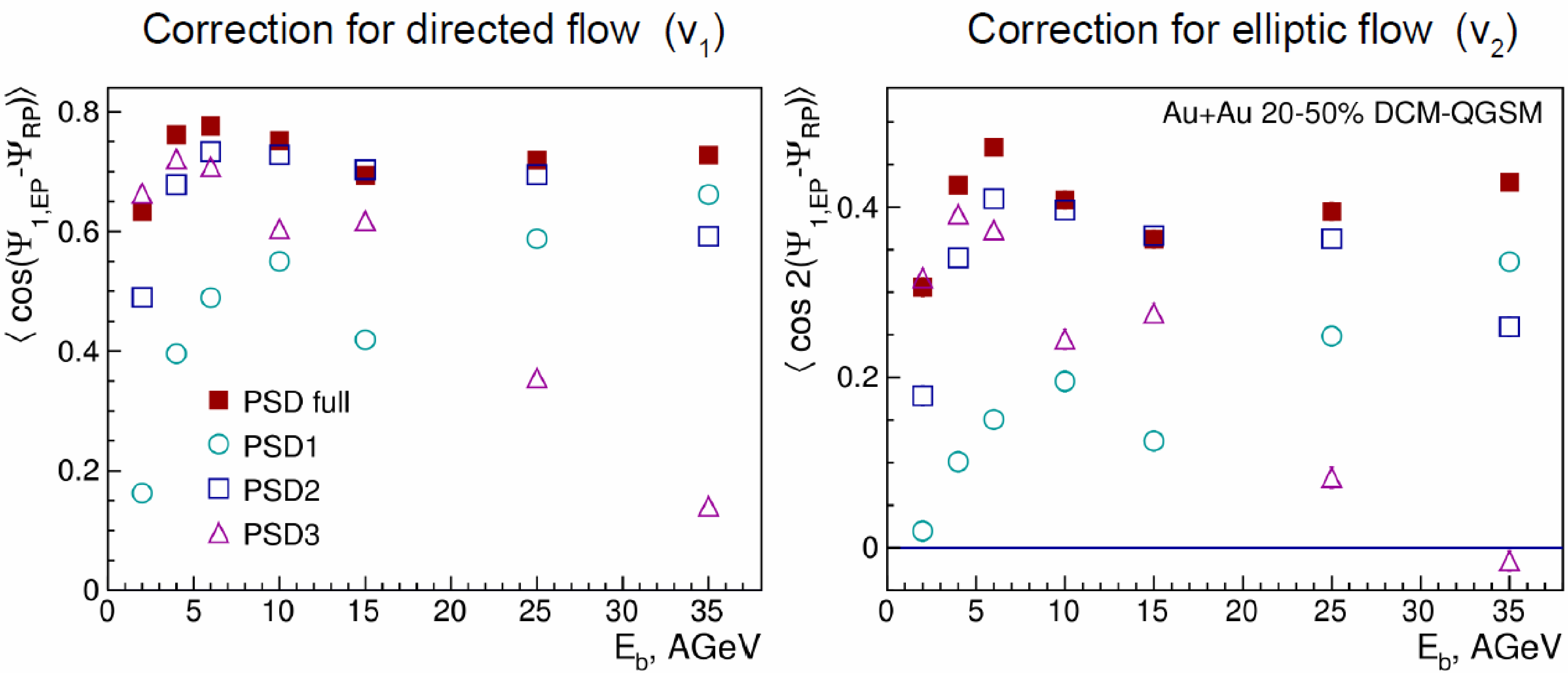
Event plane resolution before and after recentering



After corrections:

- PSD and STS event plane distributions are flattened
- PSD event plane resolution is improved and better than from STS

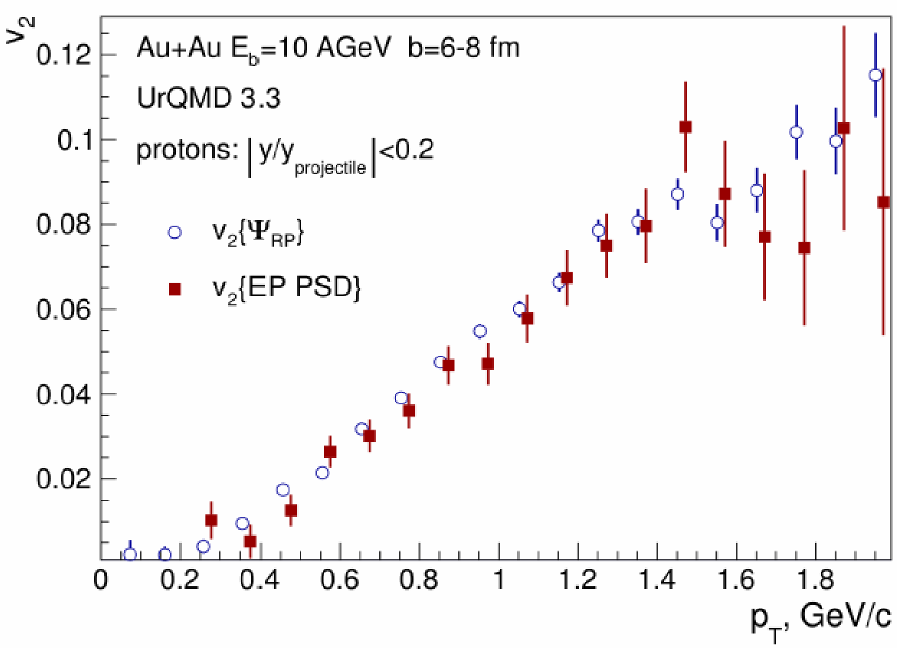
Event plane resolution (correction factor)



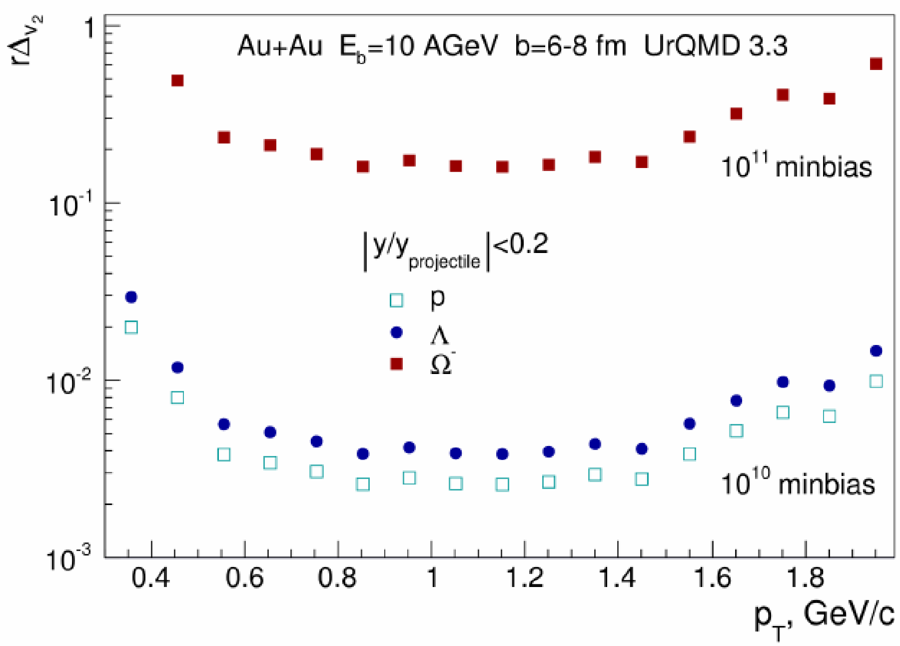
- Sensitivity of different PSD sub-events changes with collision energy
- 1st order event plane distribution is high (0.7-0.8 which is close to ideal case "1")
- 2nd order event plane resolution with PSD is good (~0.4)

PSD performance for elliptic flow (v_2) measurements

Reconstructed proton v_2 with PSD event plane correction from three PSD subevents



Statistical error projections for (strange-)baryons v_2 after 2 months of operation at 100kHz interaction rate



- "input" model v_2 is recovered using "data-driven" method with 3 PSD subevents
- Statistical error projections promises high precision measurements of (strange-)baryons v_2 in a wide p_T range between 0.3 - 2.0 GeV/c at mid-rapidity already after 2 months of CBM experiment operation