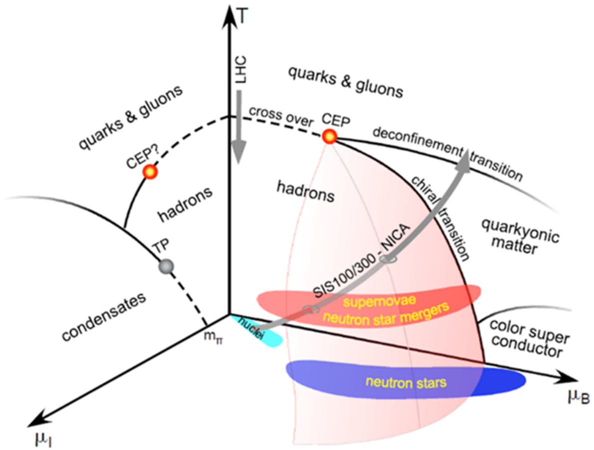
Anisotropic Flow in Heavy Ion Collisions

Viktor Klochkov

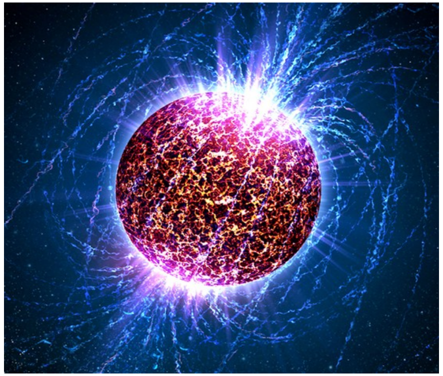
Arbeitstreffen Kernphysik 2020
Schleching, 28.02

Dense Baryonic Matter



NUPECC Long Range Plan 2017

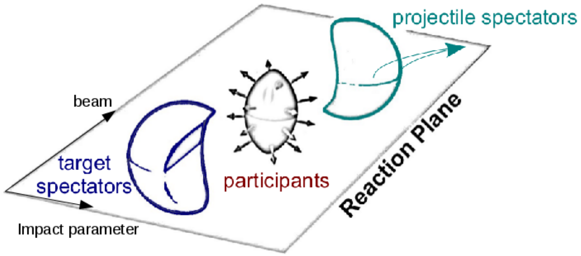
Neutron stars



Neutron star merger

GW170817

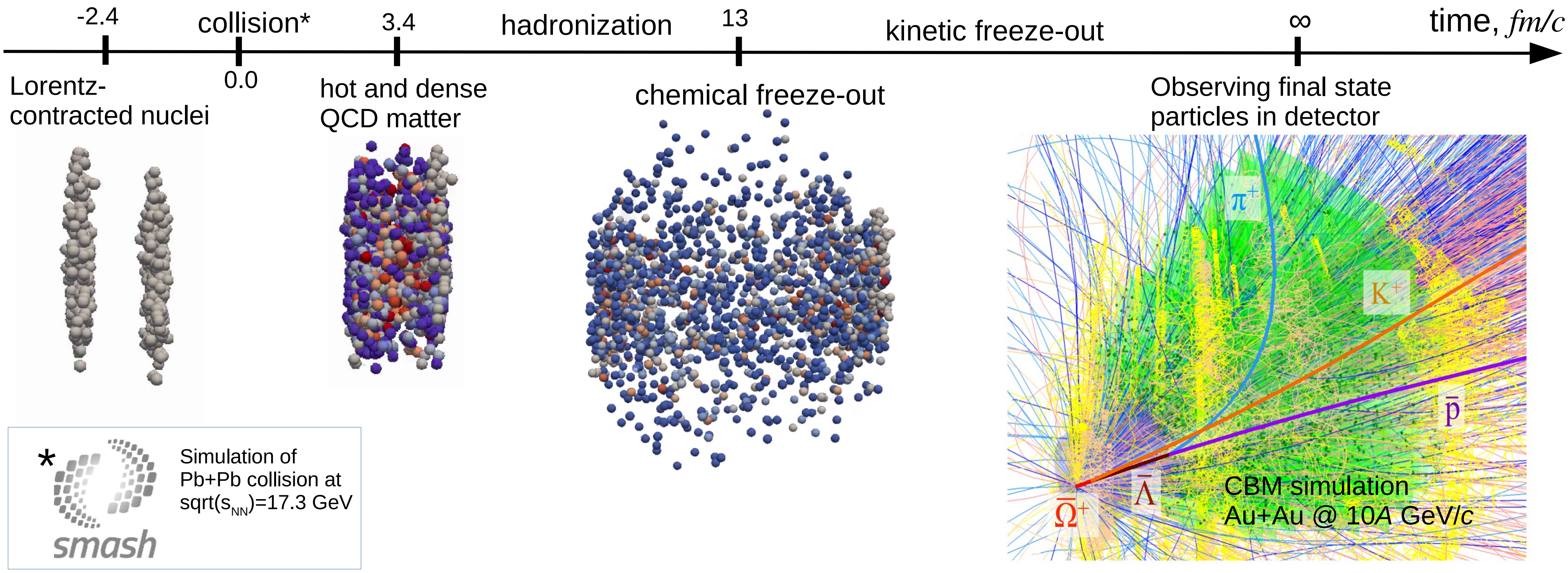
Heavy-ion collisions



at intermediate energies

Temperature (T)	< 10 MeV	~10-100 MeV	< 120-200 MeV
Density (ρ)	$< 10\ \rho_0$	$< 2\text{-}6\ \rho_0$	$< 10\ \rho_0$
Lifetime / Reaction time (t)	∞	~10 ms	$\sim 10^{-23}$ s

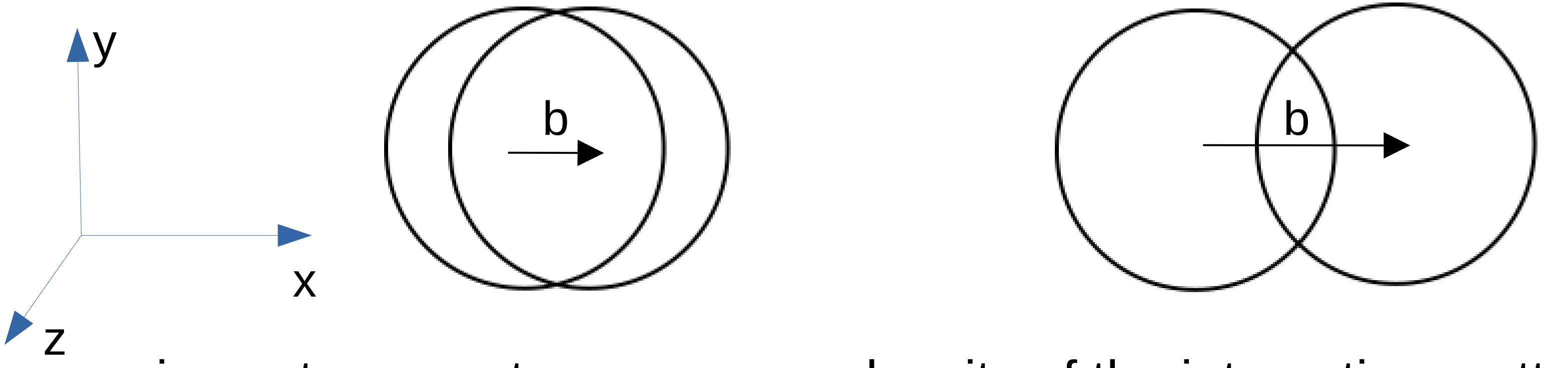
Relativistic heavy-ion collision evolution



Experimental challenge at intermediate collision energies:
reconstruct hot and dense QCD matter properties by measuring only final state particles

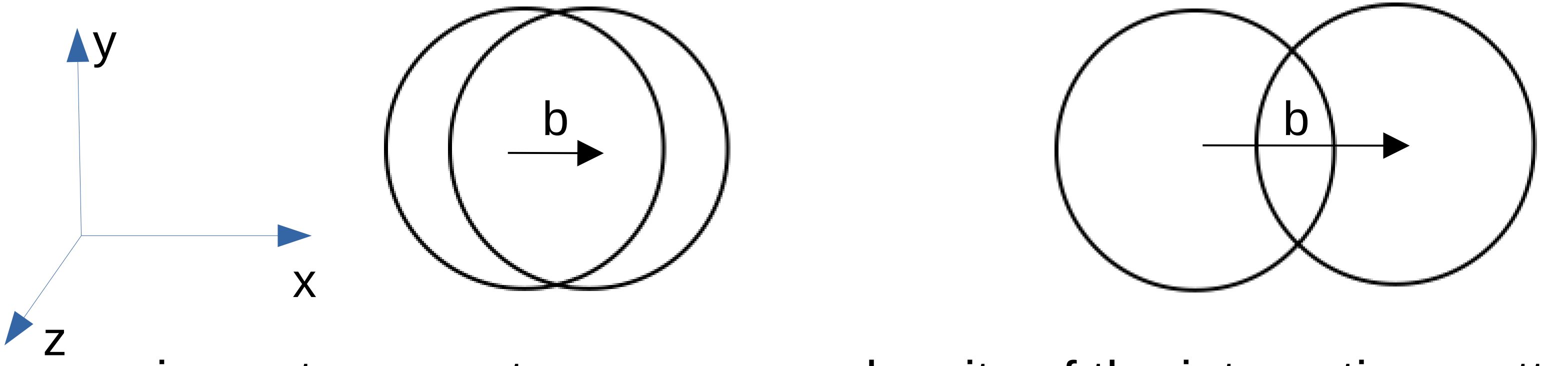
- Collision geometry and initial state fluctuations
- Interaction with “spectators”
- Medium evolution (equation of state)
- Hadronization and freeze-out

Collision geometry

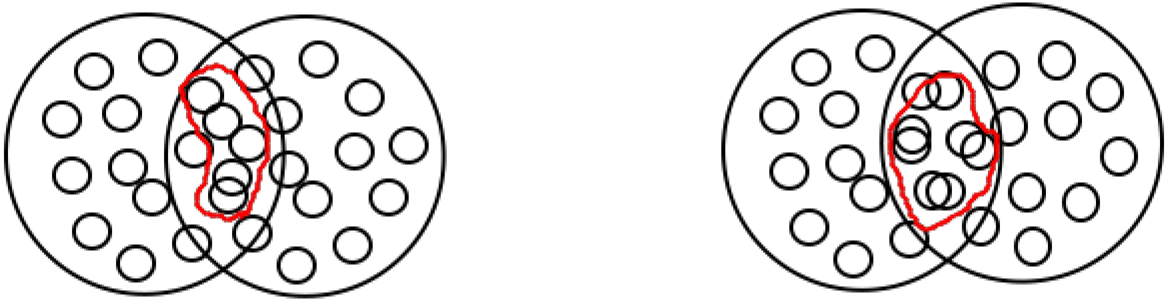


impact parameter ↔ energy density of the interacting matter

Collision geometry

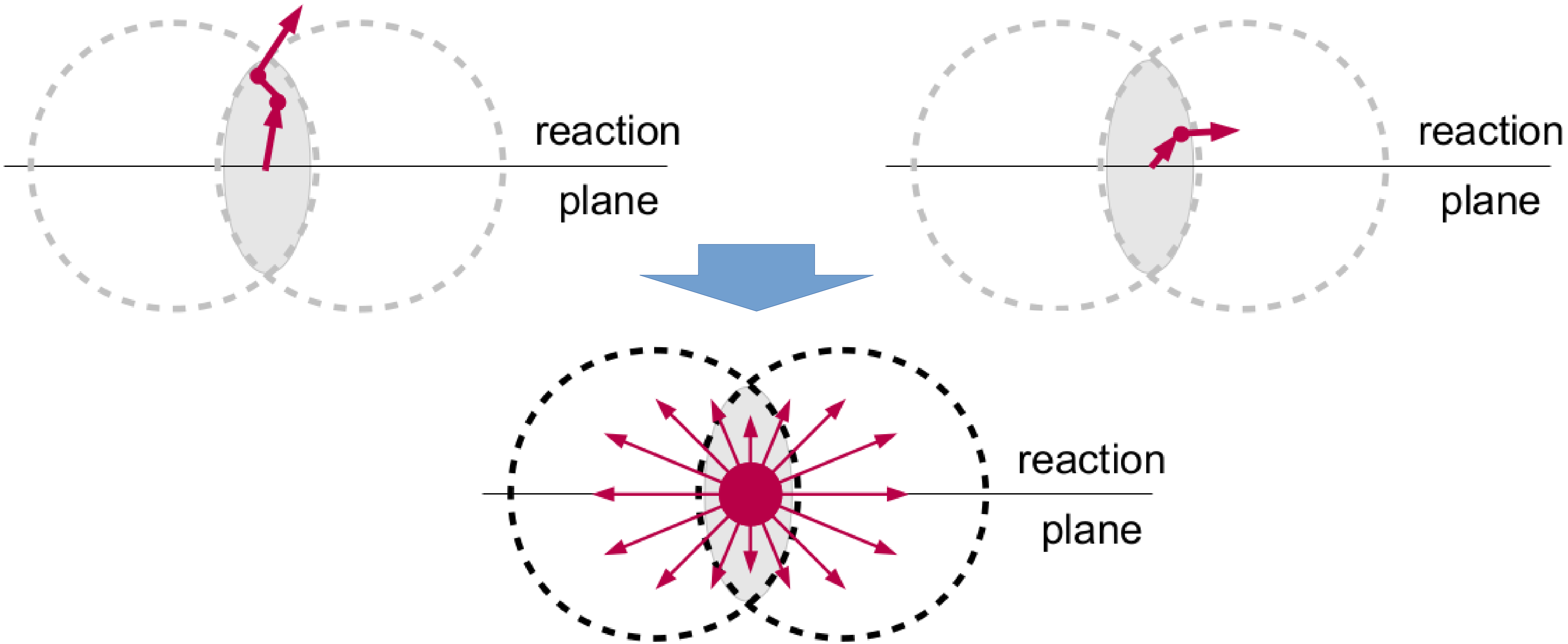


impact parameter ↔ energy density of the interacting matter



spatial asymmetry of the overlap region ↔ asymmetry of energy distribution

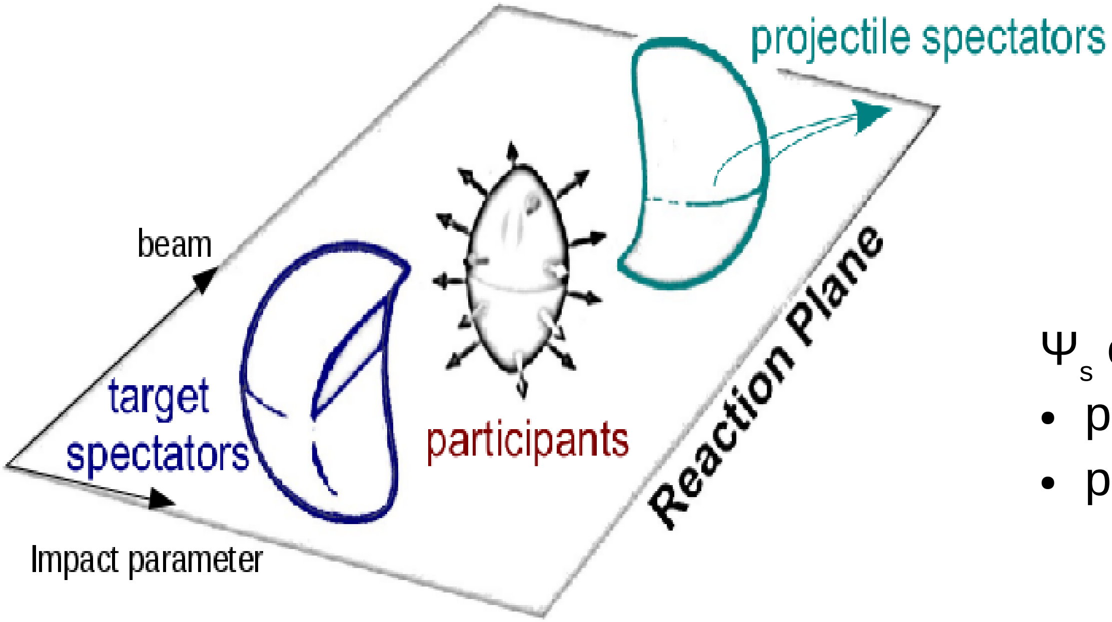
Anisotropic transverse flow



Asymmetry in initial coordinate space converts due to interaction into final momentum asymmetry with respect to the symmetry plane

Anisotropic transverse flow

Final state asymmetry is sensitive to the collision evolution and QCD matter properties



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

$$v_n=\langle\cos(n[\varphi-\Psi_s])\rangle$$

Ψ_s can be estimated from

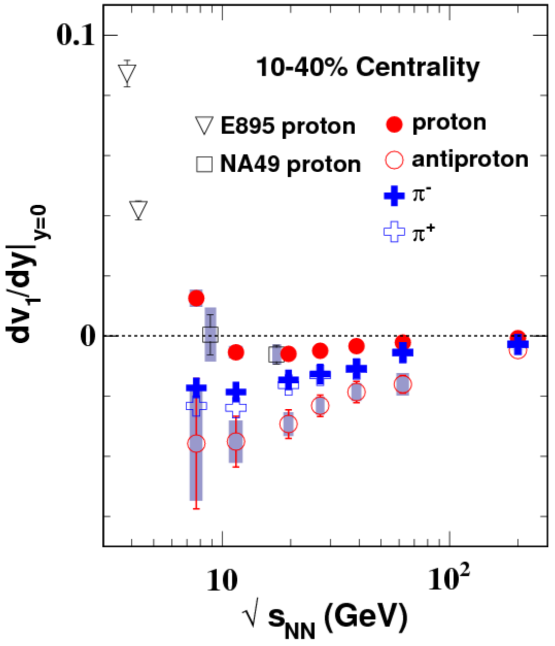
- produced particles (Ψ_{pp})
- projectile (target) spectators Ψ_{proj} (Ψ_{targ})

Important to measure flow coefficient relative
both to spectators and produced particles symmetry planes

Collective flow measurements

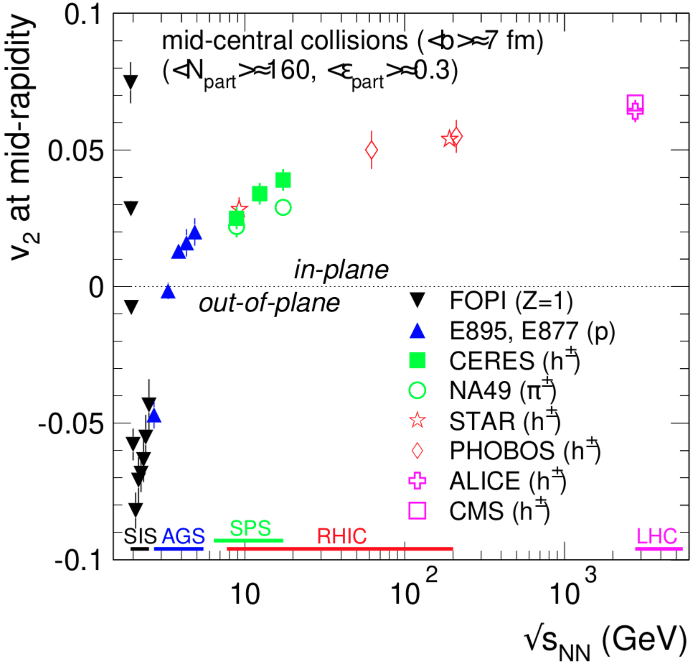
STAR Collaboration
PRL 112 (2014) 162301

Directed flow (slope)



Non-trivial behavior of directed flow associated with the change of EoS

Elliptic flow



Elliptic flow changes sign (sensitive to collision dynamics)

More results are coming soon at high μ_B region from BES-II@RHIC, NA61/SHINE@SPS and in future from CBM@FAIR MPD@NICA, ...

Flow vectors and event plane angle

u and Q-vectors:

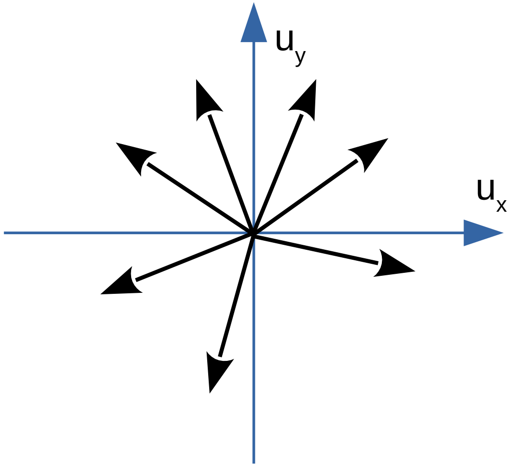
$$\vec{u}_n = \begin{pmatrix} \cos n\varphi \\ \sin n\varphi \end{pmatrix}$$

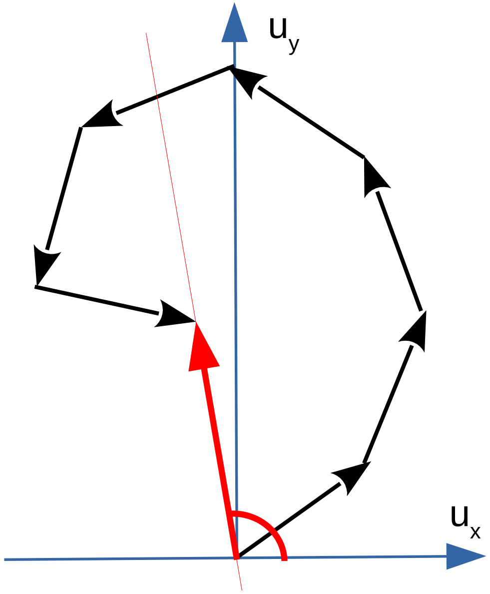
event plane method:

$$\vec{Q}_n = \frac{1}{Q_n} \sum_{j=1}^{j \le M} w_j \vec{u}_n^{\,j}$$

scalar product:

$$\vec{Q}_n = \frac{1}{M} \sum_{j=1}^{j \le M} w_j \vec{u}_n^{\,j}$$





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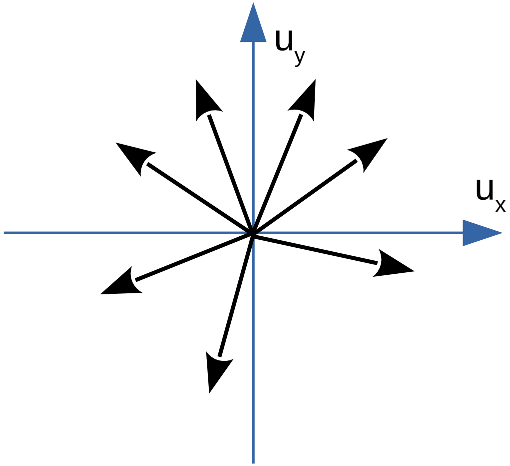

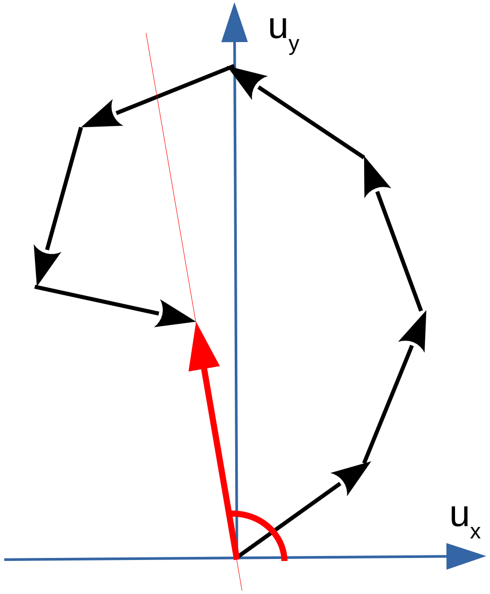

Participants event plane:

- measured with tracks
- $w_j = 1$, p_T

Spectators event plane

- usually is measured with forward calorimeters
- w_j = energy deposition in a module

Flow vectors and event plane angle

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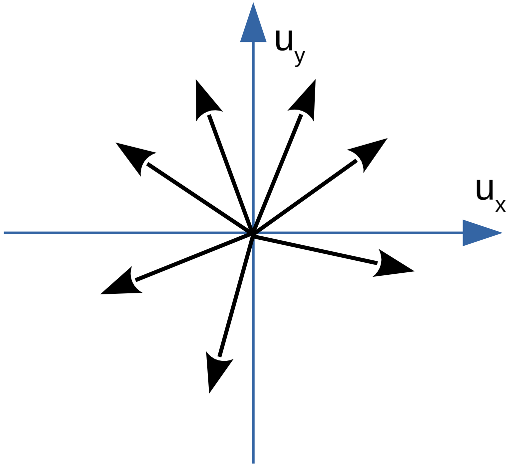
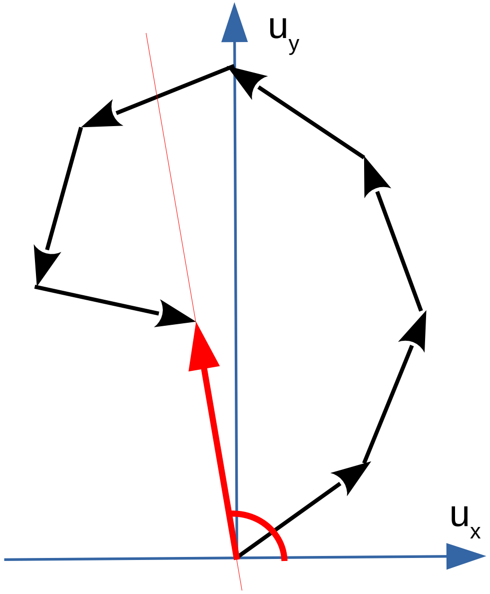




$$v_n = \langle \cos(n[\varphi - \Psi_s]) \rangle$$

Directed flow:

$$v_1 \propto \langle 2 u_{1,i} Q_{1,i} \rangle$$

Elliptic flow:

$$v_2 \propto \langle 2 u_{2,i} Q_{2,i} \rangle \approx \langle 4 u_{2,i} Q_{1,j}^{A} Q_{1,k}^{B} \rangle$$

$$(i, j, k = [x, y])$$

Resolution correction

$$v_n = \langle \cos(n[\varphi - \Psi_s]) \rangle = \frac{1}{R_{n,i}} \langle 2 u_{n,i} Q_{i,n} \rangle \qquad R_{n,i} = \langle \cos[n(\Psi_{RP} - \Psi_{EP})] \rangle$$

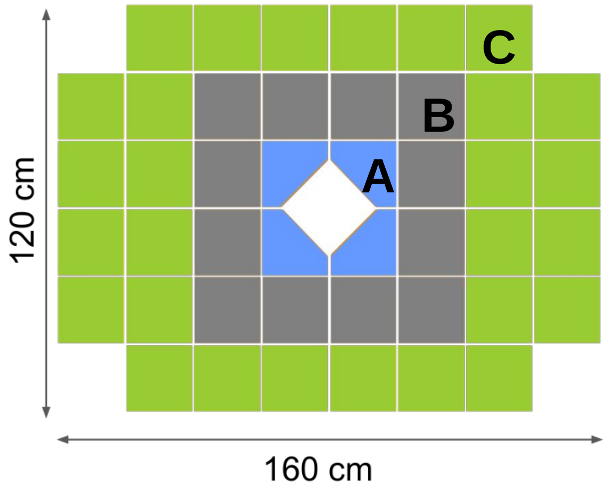
Correction factor (resolution) $R_{1,i}^{A}$ is calculated via correlations → 3-subevent method:

$$R_{1,i}^{A}[B,C] = \sqrt{2 \frac{\langle Q_{1,i}^{A} Q_{1,i}^{B} \rangle \langle Q_{1,i}^{A} Q_{1,i}^{C} \rangle}{\langle Q_{1,i}^{B} Q_{1,i}^{C} \rangle}}$$

mixed harmonics:

$$R_{1,i}^{A}[B,C,D] \propto \sqrt{\frac{\langle Q_{1,i}^{A} Q_{1,i}^{B} \rangle \langle Q_{1,i}^{A} Q_{1,i}^{C} Q_{2,i}^{D} \rangle}{\langle Q_{1,i}^{B} Q_{1,i}^{C} Q_{2,i}^{D} \rangle}}$$

CBM Projectile Spectators Detector (PSD)

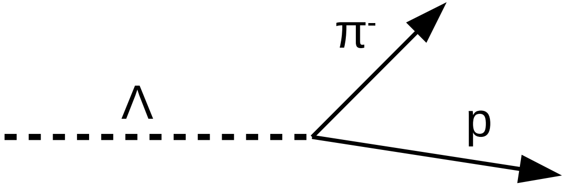


subevent A = 4 central modules

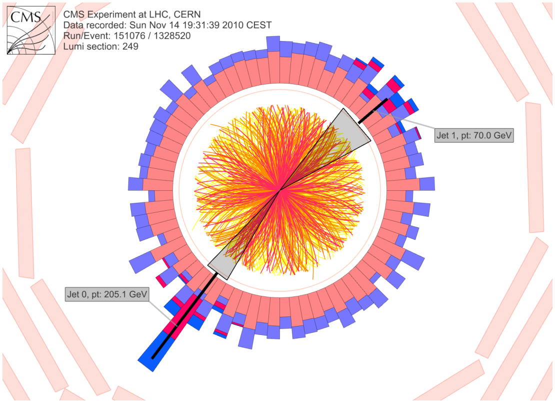
Resolution reflects the sensitivity of subevent A to initial symmetry plane

Non-flow and flow fluctuations

- Resonance decays
  - → for example, correlation between proton and pion from the lambda decay

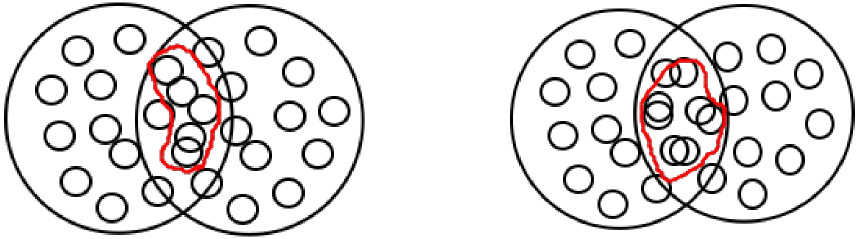


- Jets (at high enough energies)



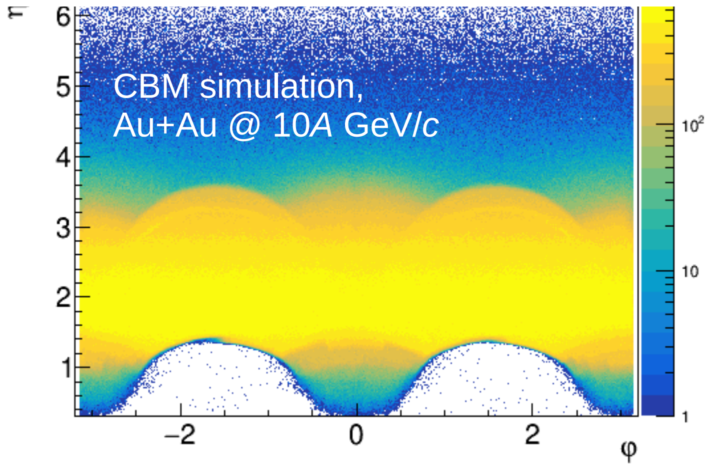
- Global momentum conservation

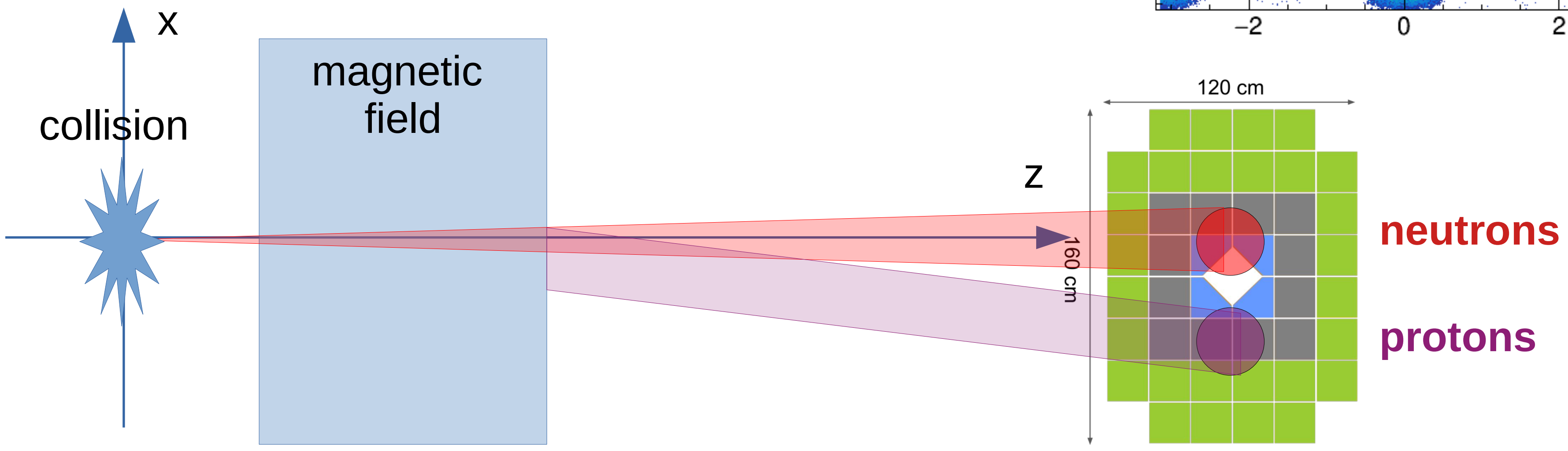
- Flow fluctuations
  - → different initial state shapes for the same impact parameter value



Detector biases

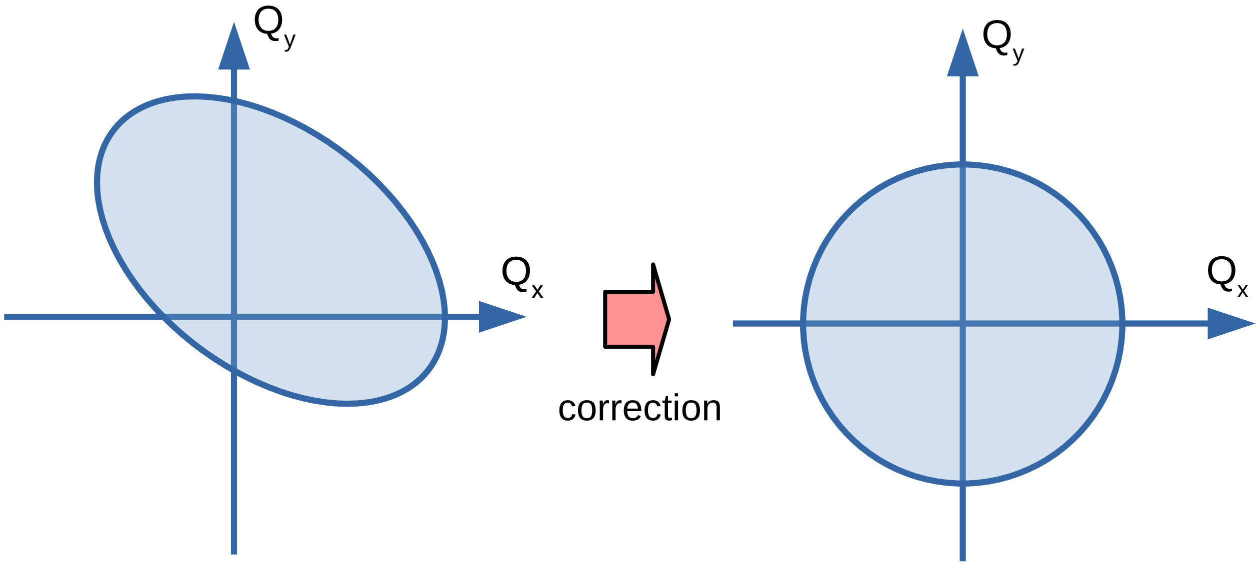
- Anisotropic detector acceptance and/or efficiency
- Magnetic field
- Tracking artefacts (track splitting etc)





Detector anisotropy introduce biases into measured azimuthal distribution

Correction for detector non-uniformity

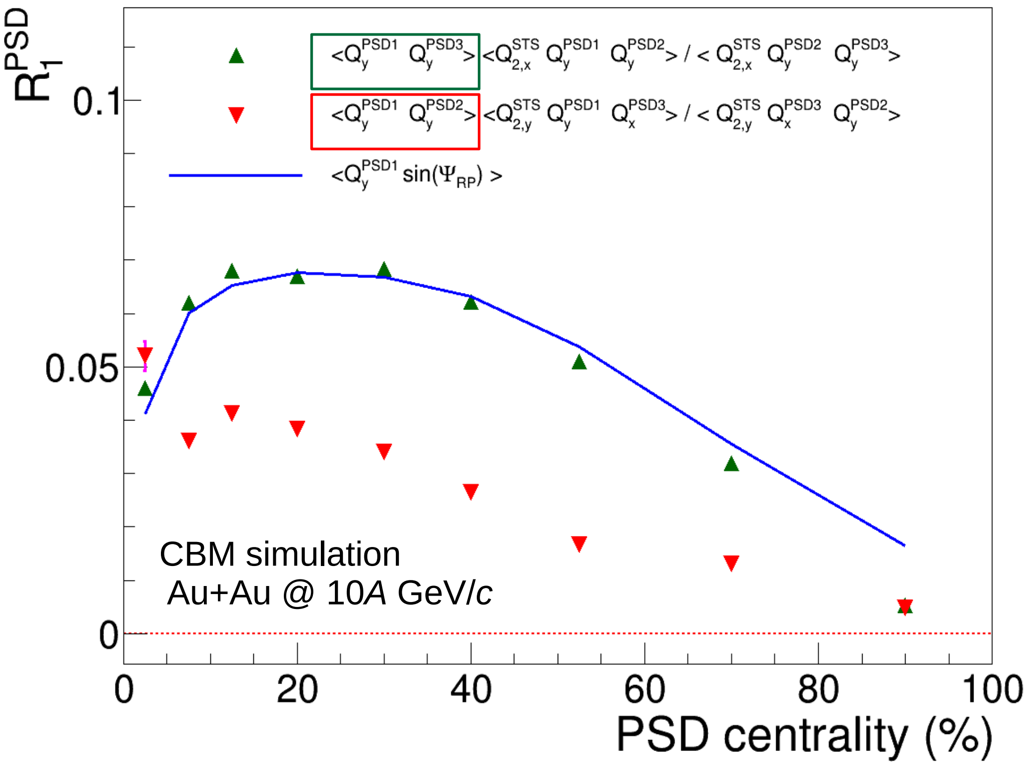


Data driven corrections for azimuthal acceptance non-uniformity
I. Selyuzhenkov and S. Voloshin
[PRC77 034904 (2008)]

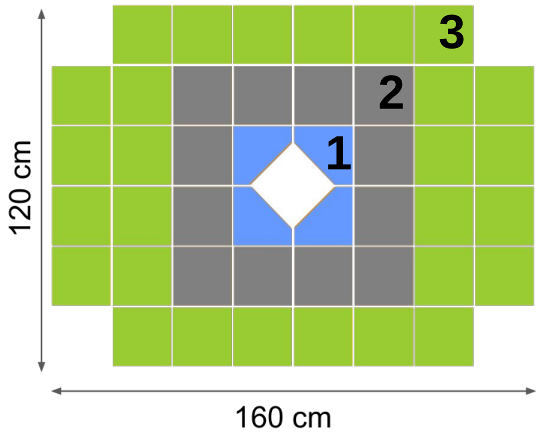
- Gain equalization
- Recentering
- Twist
- Rescaling

Correction procedure for Q-vectors is needed to recover isotropic distribution in azimuthal angle

PSD resolution correction factor

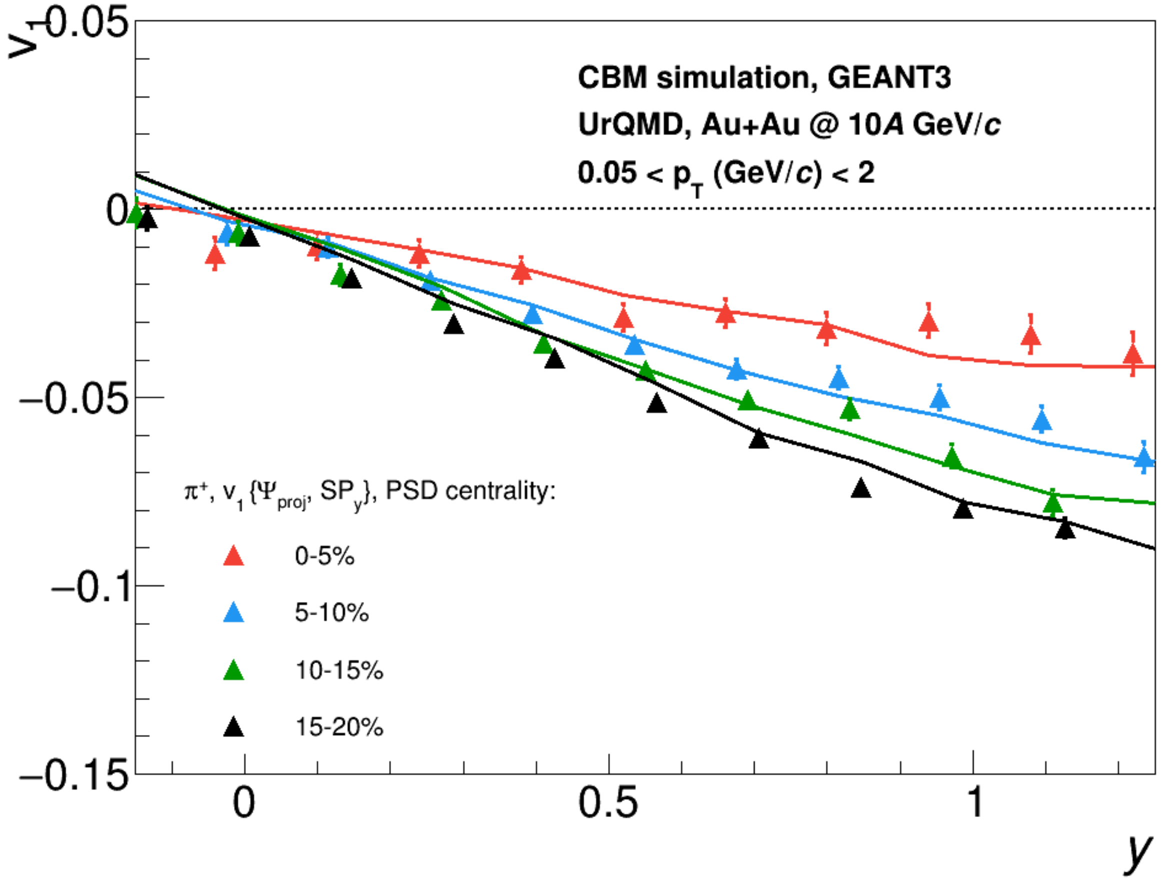


Neighboring PSD subevents correlation are distorted due to autocorrelations → mixed harmonics



After corrections we are able to reconstruct MC-true resolution correction factor

PSD performance for directed flow measurents

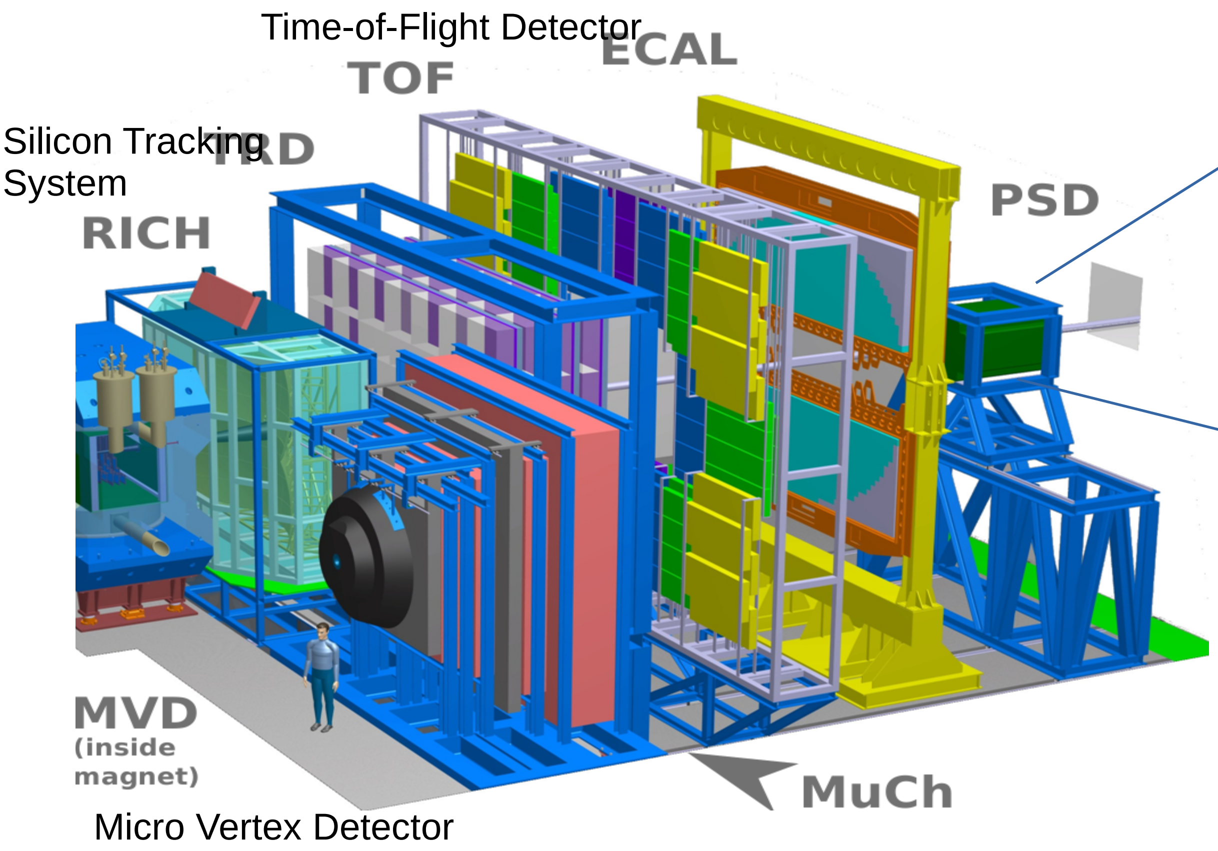


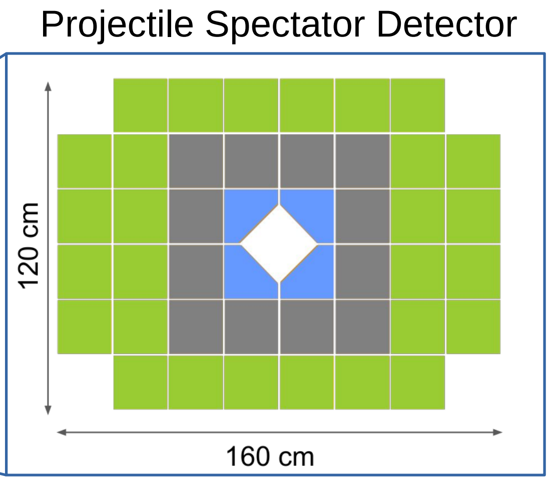
- Directed flow of positively charged pions relative to spectators plane
- Centrality is defined using energy of the projectile spectators
- Reconstructed and simulated results are consistent in all centrality bins

Summary

- Anisotropic transverse flow allows to study evolution of heavy-ion collisions and properties of QCD matter
- It is important to measure flow coefficient relative to both participants and spectators symmetry plane
- Flow measurement techniques allow for precise extraction of flow coefficients with a complicated (non-uniform) detector setup
- More results are coming soon at high μ_B region from BES-II@RHIC, NA61/SHINE@SPS and in future from CBM@FAIR MPD@NICA, ...

CBM experiment @ FAIR





Due to high interaction rates up to 10^7 beam hole is needed to avoid radiation damage

Simulation setup:
UrQMD/DCM-QGSM-SMM models,
Au+Au @ 10*A* GeV/*c*

Resolution correction

$$v_n = \langle \cos(n[\varphi - \Psi_s]) \rangle = \frac{1}{R_{n,i}} \langle 2 u_{n,i} Q_{i,n} \rangle \qquad R_{n,i} = \langle \cos[n(\Psi_{RP} - \Psi_{EP})] \rangle$$

Observables:

Directed flow:

$$v_1 = \frac{\langle 2 u_{1,i} Q_{1,i} \rangle}{R_{1,i}}$$

Elliptic flow:

$$v_2 = \frac{4 \langle u_{2,i} Q_{1,j}^{A} Q_{1,k}^{B} \rangle}{R_{1,j}^{A} R_{1,k}^{B}}$$

$$i, j, k = [x, y]$$

Correction factor (resolution) $R_{1,i}^{A}$ is calculated via correlations → 3-subevent method:

$$R_{1,i}^{A}[B,C] = \sqrt{2 \frac{\langle Q_{1,i}^{A} Q_{1,i}^{B} \rangle \langle Q_{1,i}^{A} Q_{1,i}^{C} \rangle}{\langle Q_{1,i}^{B} Q_{1,i}^{C} \rangle}}$$

mixed harmonics:

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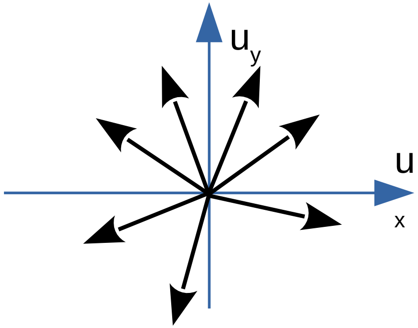
Resolution shows the sensitivity of subevent A to initial symmetry plane



Multiparticles azimuthal correlations

$$v_n = \langle \cos n(\varphi - \Psi_n) \rangle$$

- Estimating flow harmonics with 2-particle correlation:

event average

particle average

$$\left\langle\left\langle e^{in(\varphi_1-\varphi_2)} \right\rangle\right\rangle = \left\langle\left\langle e^{in(\varphi_1-\Psi_n-(\varphi_2-\Psi_n))} \right\rangle\right\rangle$$

$$= \left\langle\left\langle e^{in(\varphi_1-\Psi_n)} \right\rangle\left\langle e^{-in(\varphi_2-\Psi_n)} \right\rangle\right\rangle$$

$$= v_n^2$$

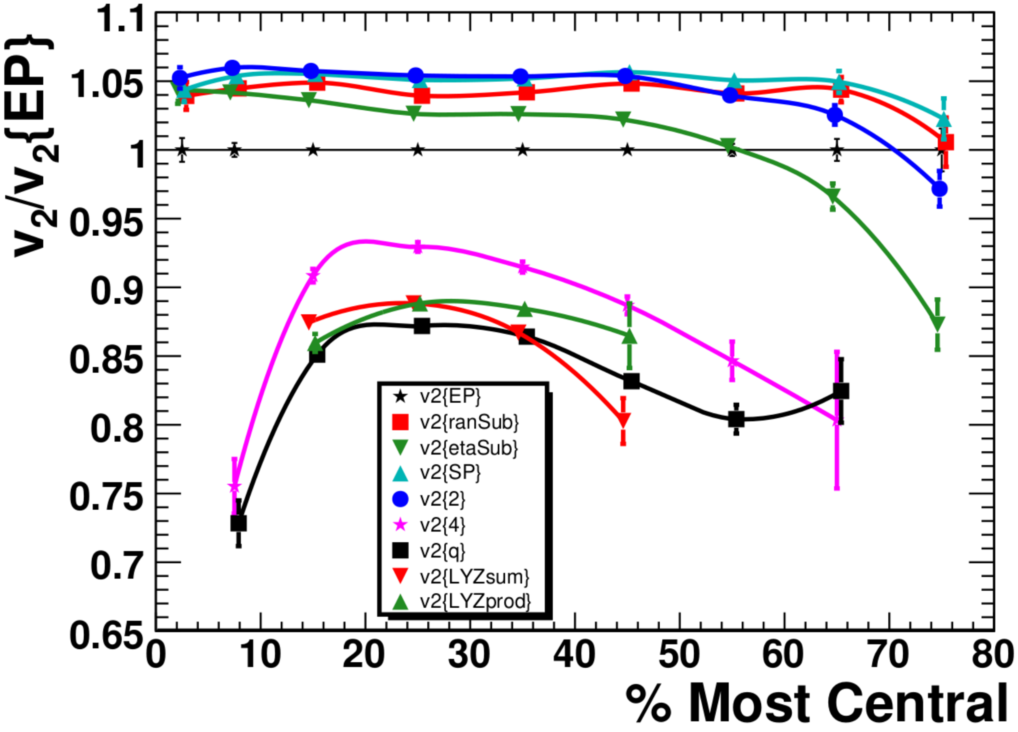
- The 'trick' works for any number of particles in the correlator

Ante

Methods comparison

$$\vec{Q}_n = \frac{1}{Q_n} \sum_{j=1}^{j \le M} \vec{u}_n^{\,j} \quad \Rightarrow \quad \vec{Q}_n = \frac{1}{M} \sum_{j=1}^{j \le M} \vec{u}_n^{\,j}$$

different sensitivity to non-flow



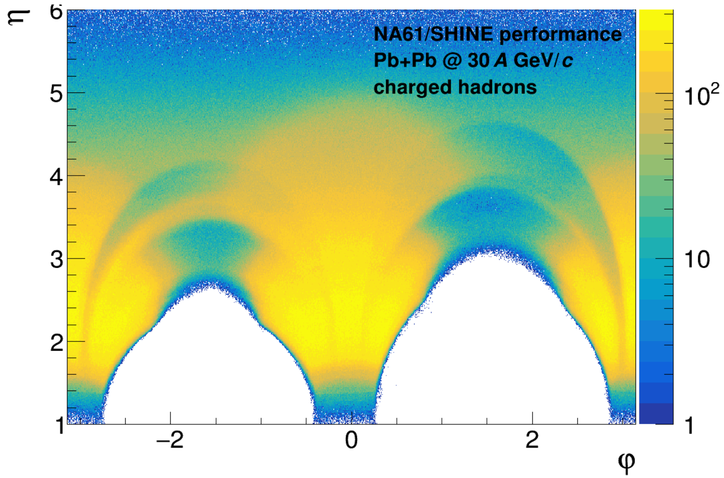
Upper band → two-particle correlation

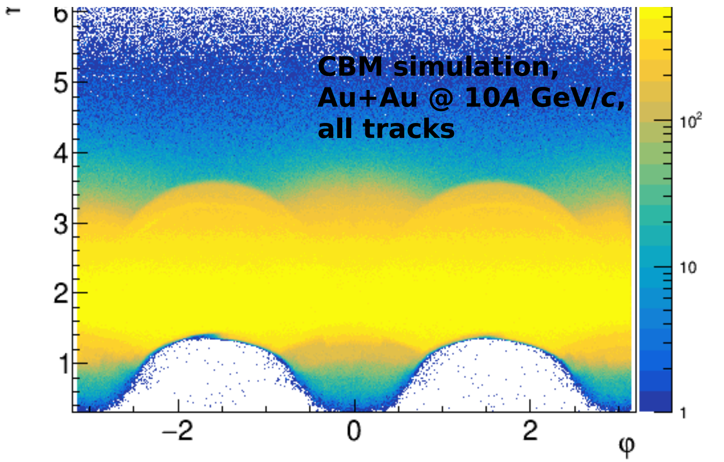
- averages along the participant plane with nonflow and fluctuation contributions

Lower band → multi-particle correlation

- averages along the reaction plane mostly free of nonflow and fluctuation contributions

Framework for detector azimuthal non-uniformity corrections and analysis





QnVector Corrections Framework

- Data driven corrections for azimuthal acceptance non-uniformity
  I. Selyuzhenkov and S. Voloshin [PRC77 034904 (2008)]
- QnVector Corrections Framework (used by ALICE)
  J. Onderwaater, V. Gonzalez, I. Selyuzhenkov
  https://github.com/jonderwaater/FlowVectorCorrections

ALICE

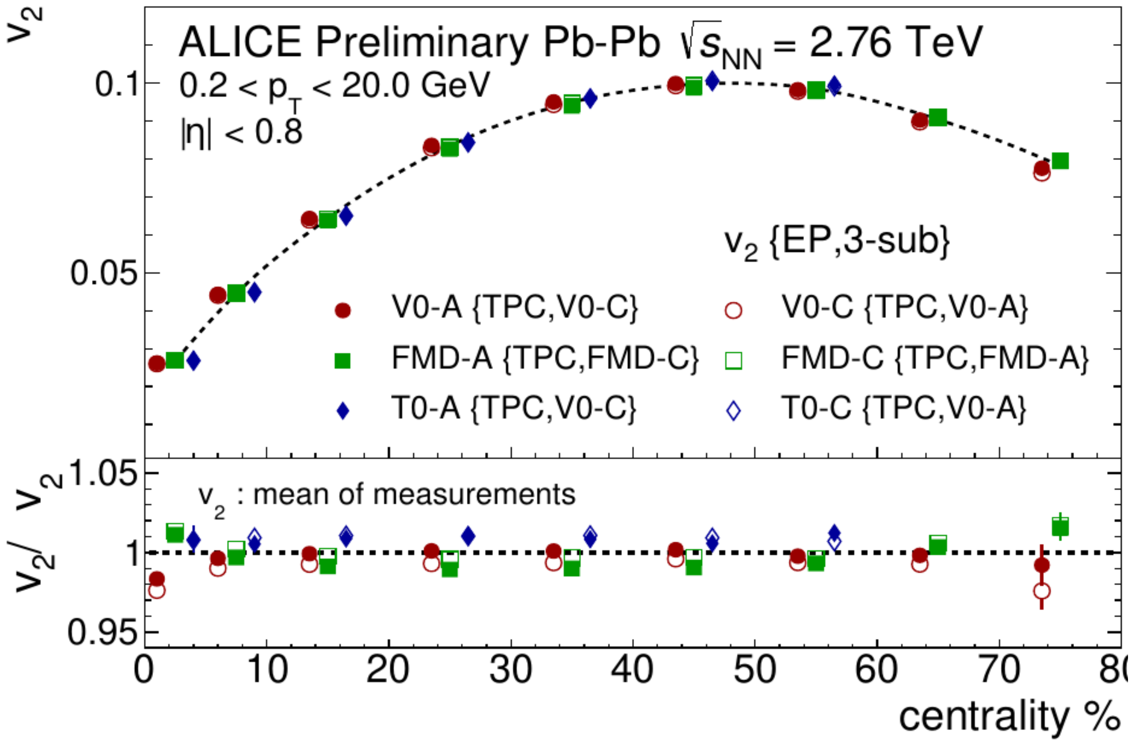
- Recentering, twist, and rescaling corrections applied
  time dependent (run-by-run) and as a function of centrality

Flow Analysis Framework

- Extended Q_n-vector corrections for p_T/y-differential
- Multi-dimensional correlations of u and Q-vectors
  L. Kreis (GSI / Heidelberg) and I. Selyuzhenkov (GSI / MEPhI)

Interfaced to CBM and NA61/SHINE analysis environment

Framework for detector azimuthal non-uniformity corrections



- After corrections, the elliptic flow measurements with different event plane estimators are fully consistent with each other

QnVector Corrections Framework (ALICE)
J. Onderwaater, V. Gonzalez, I. Selyuzhenkov

https://github.com/jonderwaater/FlowVectorCorrections