Collective phenomena at RHIC and LHC

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Facets of Strong-Interaction Physics

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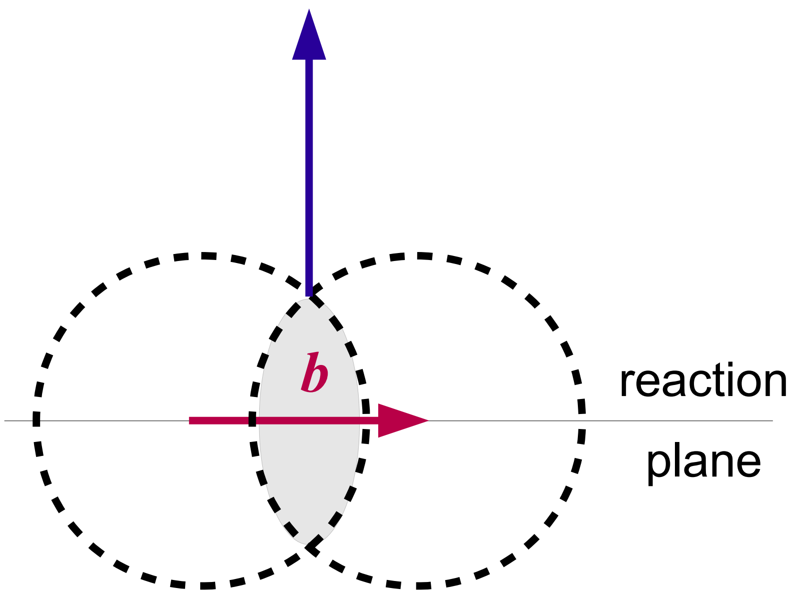
Non-central relativistic heavy-ion collision (HIC)

B - magnetic field

L - orbital momentum



b – impact parameter

Colliding nuclei are moving out-of-plane

- Overlap area:
  non-uniform particle density
  and pressure gradient

- Large orbital angular momentum:

$$\mathbf{L} \sim 10^5\, \hbar$$

Liang, Wang, PRL94:102301 (2005)
Liang, JPG34:323 (2007)

- Strong magnetic field:

$$\mathbf{B} \sim 10^{15}\,\mathrm{T} \quad (e\mathbf{B} \sim 10^4\,\mathrm{MeV}^2)$$

$$(\mu_N \mathbf{B} \sim 100\,\mathrm{MeV})$$

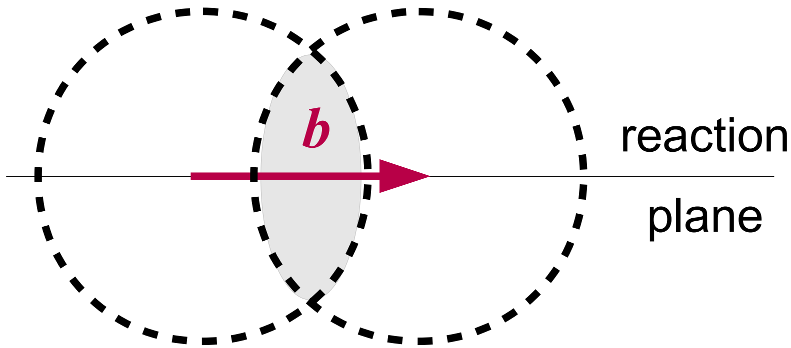
Rafelski, Müller PRL36:517 (1976)
Kharzeev, PLB633:260 (2006)
Kharzeev, McLerran, Warringa NPA803:227 (2008)

Anisotropic transverse flow

- What is anisotropic flow and why do we measure it?
- Measurement techniques: correlations and non-flow
- Elliptic flow at RHIC and LHC
- Flow fluctuations and higher harmonics

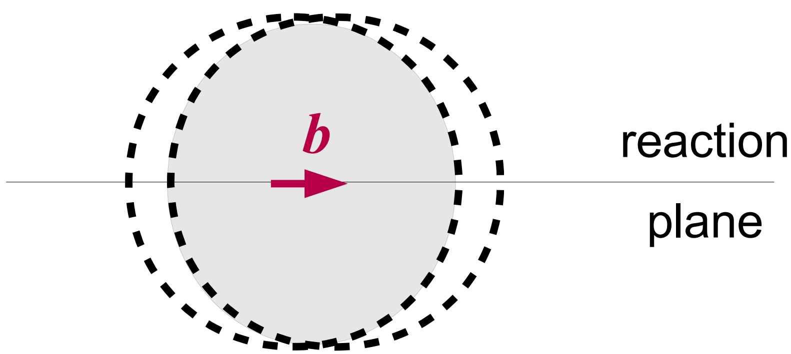
Colliding nuclei has a finite size

Peripheral collision (large ***b***)



Overlap region is strongly asymmetric in the transverse plane

Central collision (small ***b***)



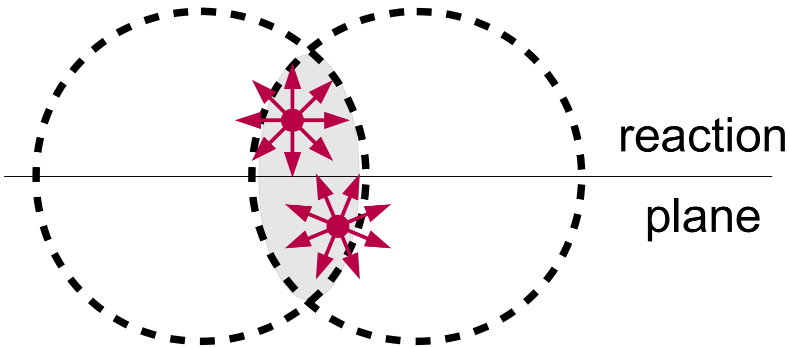
Overlap region is close to be symmetric in the transverse plane

Asymmetry of the overlap region depends on the impact parameter

b - impact parameter

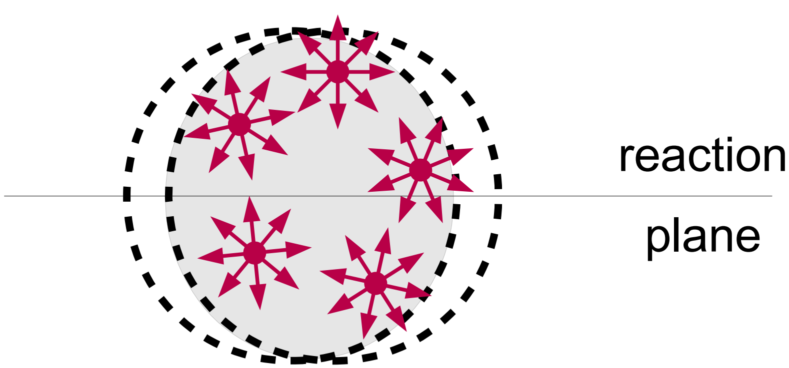
Nucleon-nucleon collisions in the overlap region

Peripheral collision



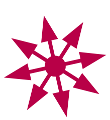
Small number of nucleon-nucleon collisions:
few particles produced

Central collision



Large number of NN collisions:
abundant particle production

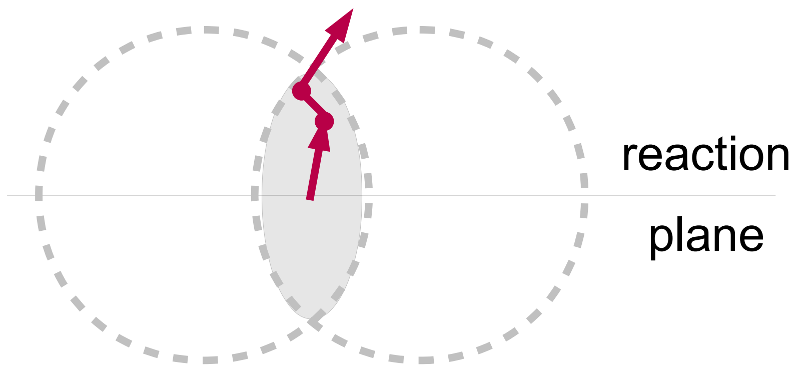
Number of produced particles
is correlated with the impact parameter



- elementary nucleon-nucleon (NN) collision

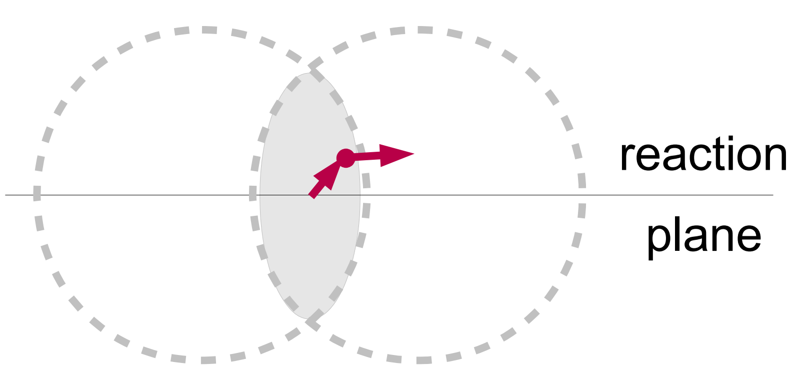
Produced particles interact with each other

Particle emitted out-of-plane



Multiple interaction with medium

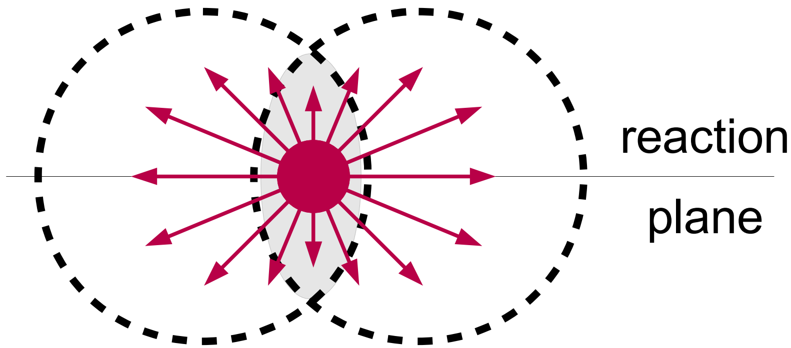
Emitted in-plane



Less interaction - small modification

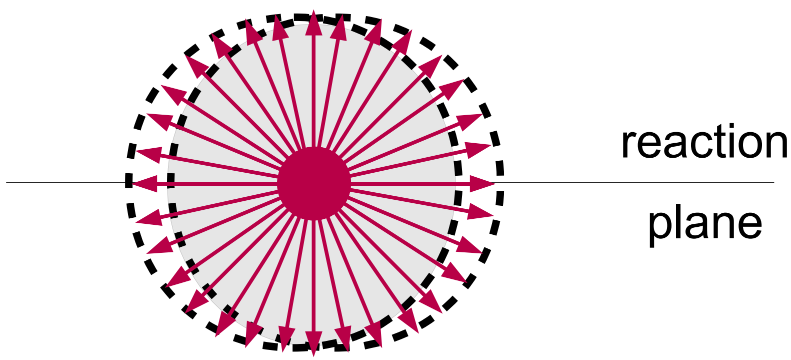
Particle collectivity

Peripheral collision



Strong coordinate space asymmetry transforms into the azimuthal asymmetry in the momentum space

Central collision



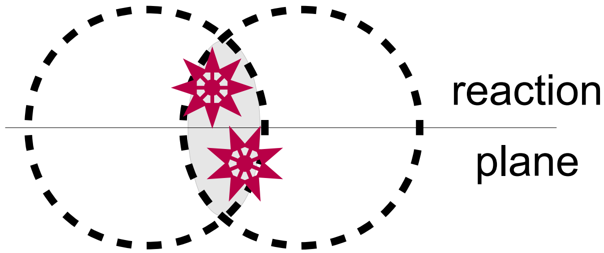
Multiple interaction with medium but small initial spacial asymmetry:
small asymmetry in the momentum space

Correlated particle production
wrt. the collision plane of symmetry

Quantifying azimuthal asymmetry

Coordinate space asymmetry is ~ ellipsoidal
quantified by eccentricity:

$$\epsilon_s = \frac{\langle y^2 - x^2 \rangle}{\langle y^2 + x^2 \rangle}$$



x, y - position of each elementary NN interaction

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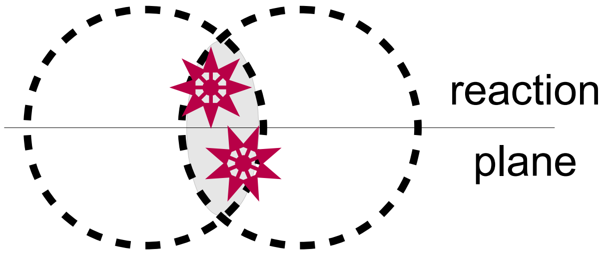
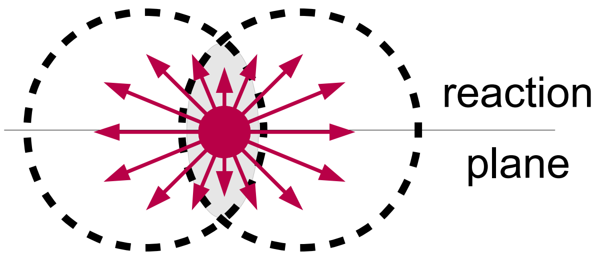


x, y - position of each elementary NN interaction

Momentum space asymmetry:

$$e_p \sim \frac{\langle p_x^2 - p_y^2 \rangle}{\langle p_y^2 + p_x^2 \rangle} \rightarrow \langle \cos(2\Delta\phi) \rangle$$

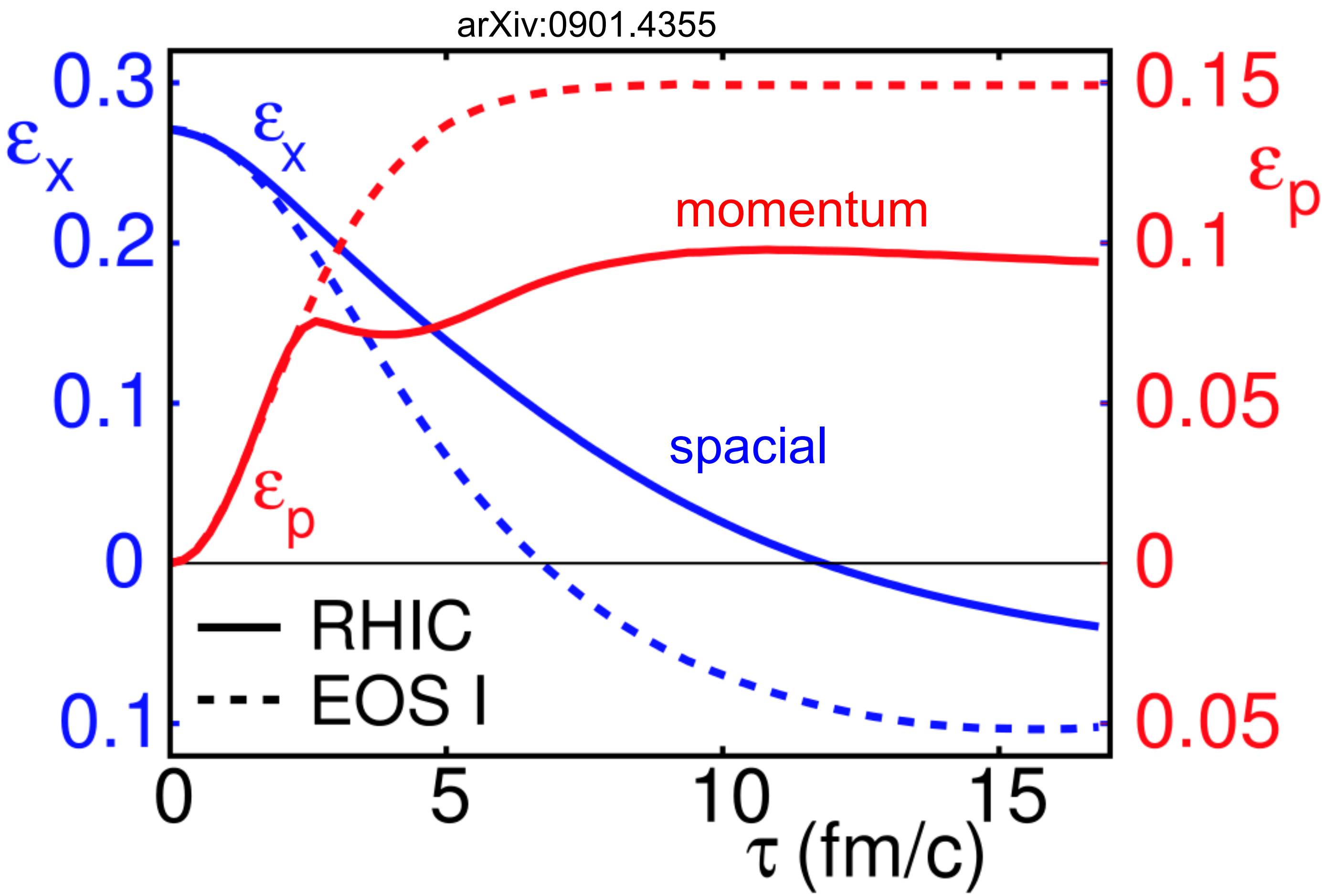


Second Fourier harmonic in momentum space

p_t - particle transverse momentum

$\Delta\phi$ - azimuthal angle relative to the reaction plane

Time evolution of the spacial and momentum asymmetries



Spacial asymmetry drops very fast

Momentum asymmetry develops very early

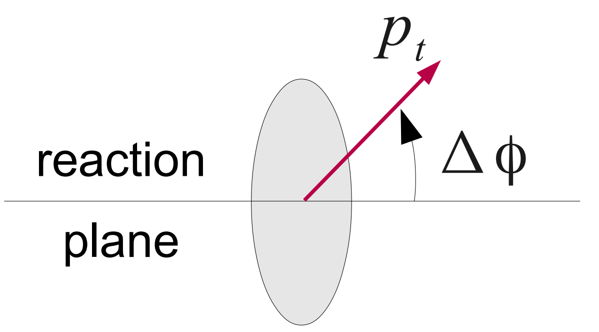
EoS I: massless ideal gas
EoS RHIC: matching Lattice QCD

Momentum asymmetry is sensitive to:

- Early times of the system evolution
- Equation of State

Anisotropic transverse flow: Fourier harmonics

Fourier decomposition of the particle azimuthal distribution wrt. the reaction plane:



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

No “sin” terms because of the collision symmetry

$v_n(p_t,\eta)$ – anisotropic transverse flow coefficients

v_1 - directed flow

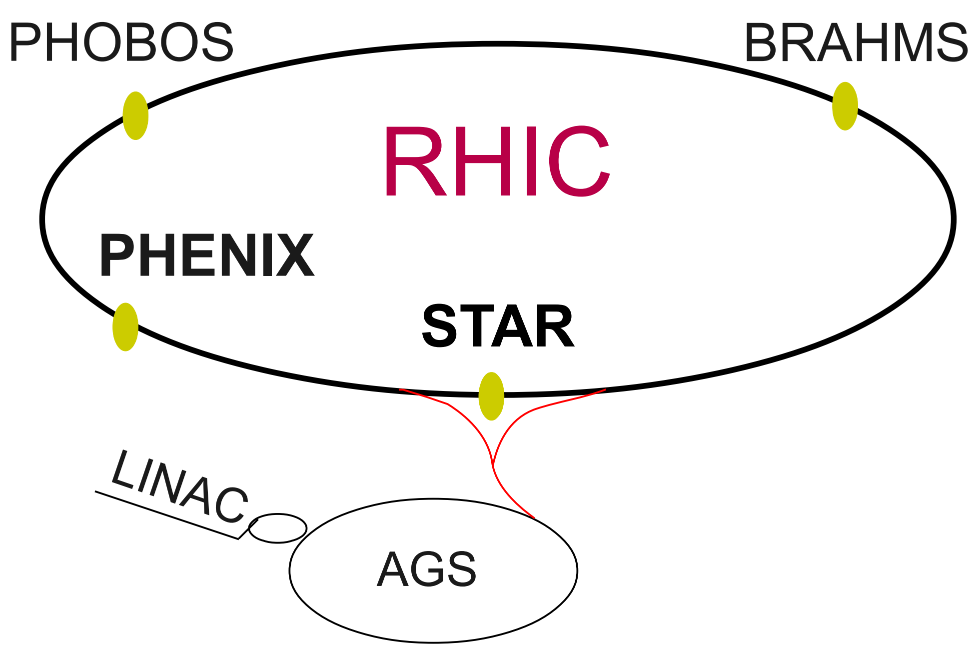
v_2 - elliptic flow

v_3 - triangular flow

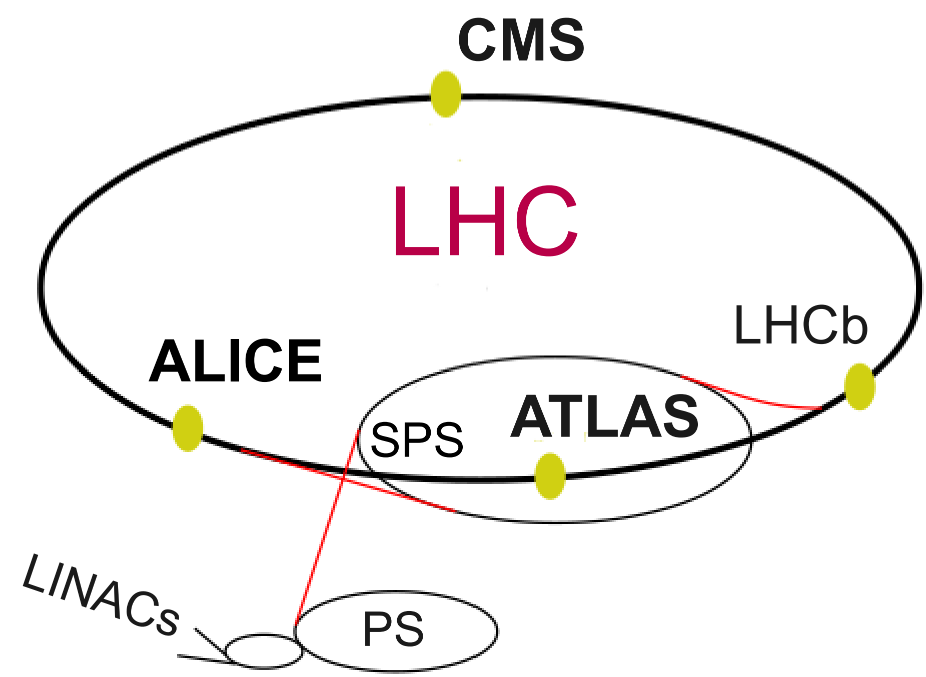
Experimental measurements of the anisotropic flow

Modern ultra-relativistic HI colliders

Relativistic Heavy Ion Collider



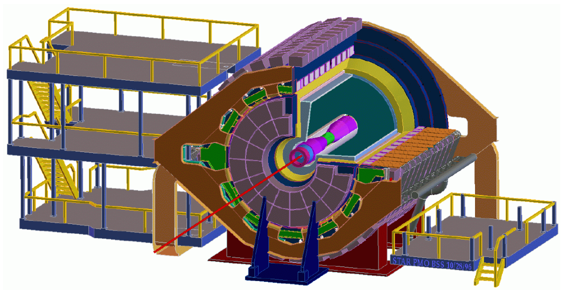
Large Hadron Collider



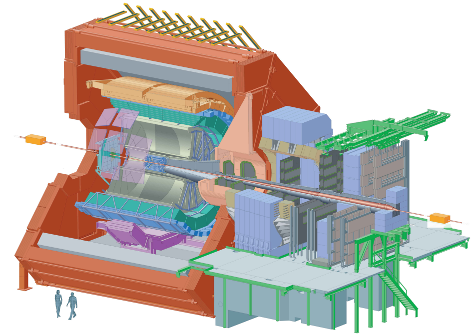
	RHIC	LHC
Location	BNL (USA)	CERN (Europe)
Circumference	3.8 km	27 km
Species	p, d, Cu, Au, U polarized protons	p, Pb
Center of mass energy per nucleon pair	in GeV 7.7-38, 62, 200 500 (pp only)	in TeV 0.9, 2.76, 7 (pp) 2.76 (Pb)

Current heavy-ion experiments at RHIC and LHC

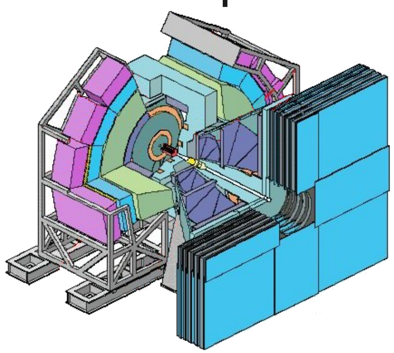
STAR (Solenoidal Tracker At RHIC)



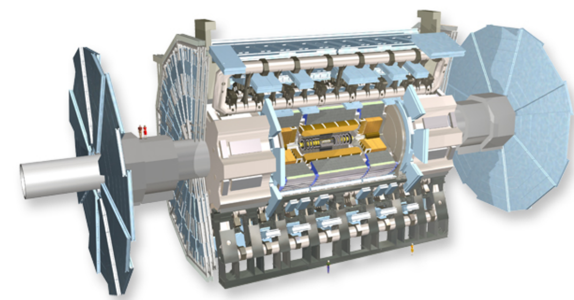
ALICE (A Large Ion Collider Experiment)



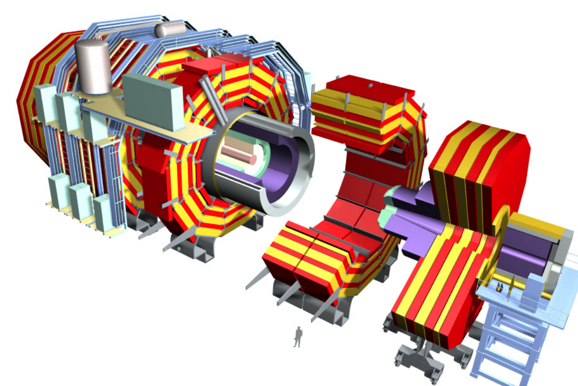
PHENIX (Pioneering High Energy Nuclear Ion Experiment)



ATLAS (A Toroidal LHC Apparatus)



CMS (Compact Muon Solenoid)



Main capabilities for heavy-ion studies:

Charge particle tracking and identification:
- full azimuth, large rapidity coverage
- wide p_t range: ~ 100 MeV/c to ~ 100 GeV/c

Calorimetry and rare probes:
- neutral particles, photons, jets, heavy flavor

Anisotropic flow measurement techniques

$$\frac{dN}{d\left(\phi_i - \Psi_{RP}\right)} \sim 1 + 2 \sum_{n=1} v_n \cos\left[n\left(\phi_i - \Psi_{RP}\right)\right]$$

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

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

Anisotropic flow measurement techniques

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

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

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Event plane angle - experimental estimate of the reaction plane angle based on the measured azimuthal distribution of particles:

$$\Psi_{RP} \rightarrow \Psi_{EP} \left\{ \sum_{\phi_j} g(\phi_j) \right\}$$

$$v_n^{obs} = \langle \cos[n(\phi_i - \Psi_{EP})] \rangle \sim \langle \sum_{\phi_j \neq \phi_i} \cos n(\phi_i - \phi_j) \rangle$$

$$c_n\{2\} = \langle \cos n(\phi_i - \phi_j) \rangle$$

- two particle correlations

Measure anisotropic flow with azimuthal correlations

Non-flow correlations

Non-flow: correlations among the particles unrelated to the reaction plane

In case of two particle correlations: $\langle \cos[n(\phi_i - \phi_j)] \rangle = \langle v_n^2 \rangle + \delta_{2,n}$

Sources of non-flow correlations:

- Resonance decay
- Jet production
- In general - any cluster production

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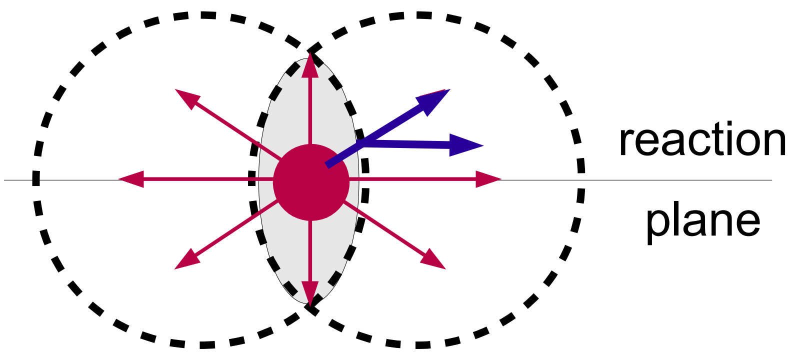
Example: 2-particle decay



Collective flow:
correlations between particles through the common plane of symmetry

Probability to be correlated for one particle with another out of M-particles is $1/(M-1)$:

$$\delta_2 \sim \frac{1}{M-1}$$

To measure flow with 2-particle correlations:

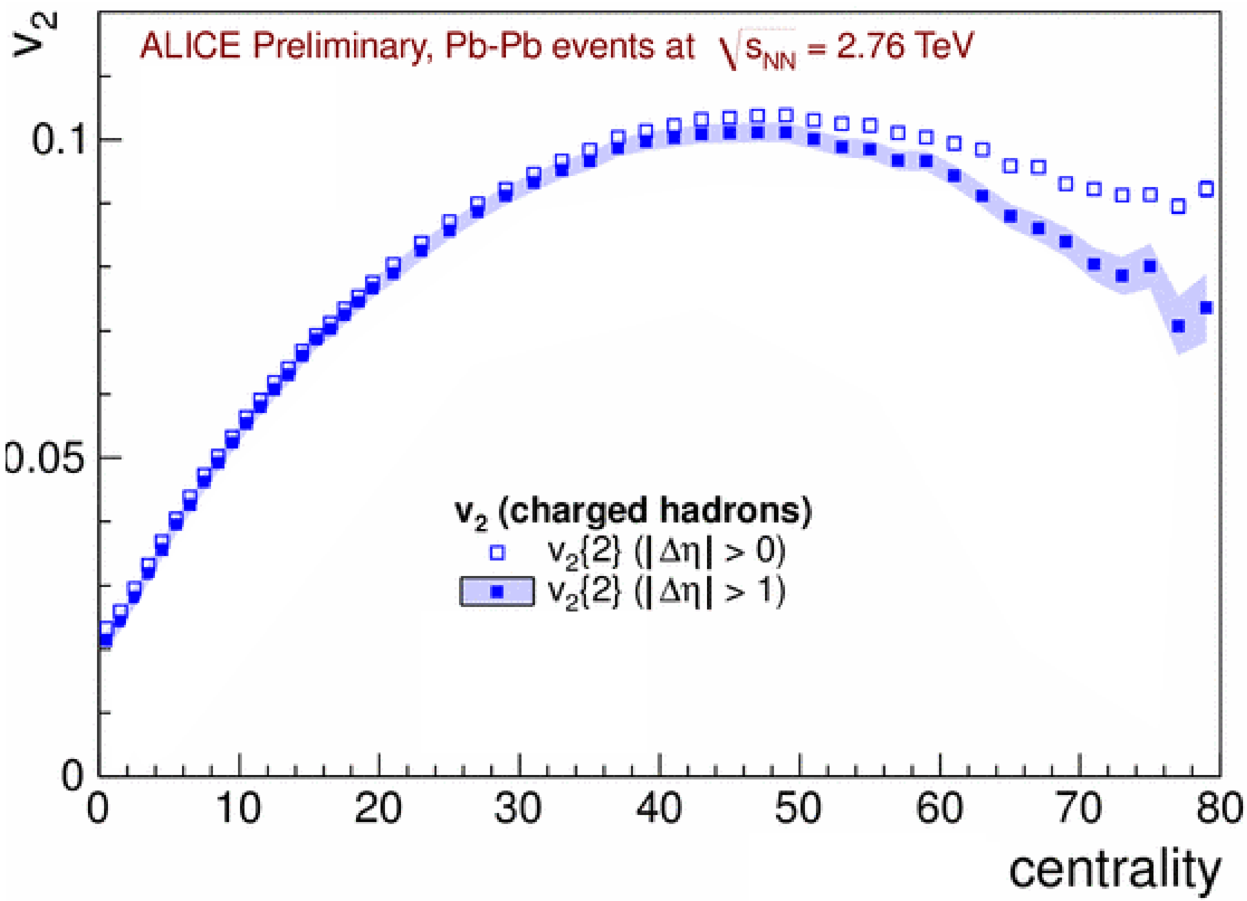
$$v_n \gg 1/\sqrt{M}$$

$$M = 200 \rightarrow v_n \gg 0.07$$

For RHIC/LHC: $v_n \approx 0.04 - 0.07$

Estimating flow with multi-particle cumulants

elliptic flow vs. centrality



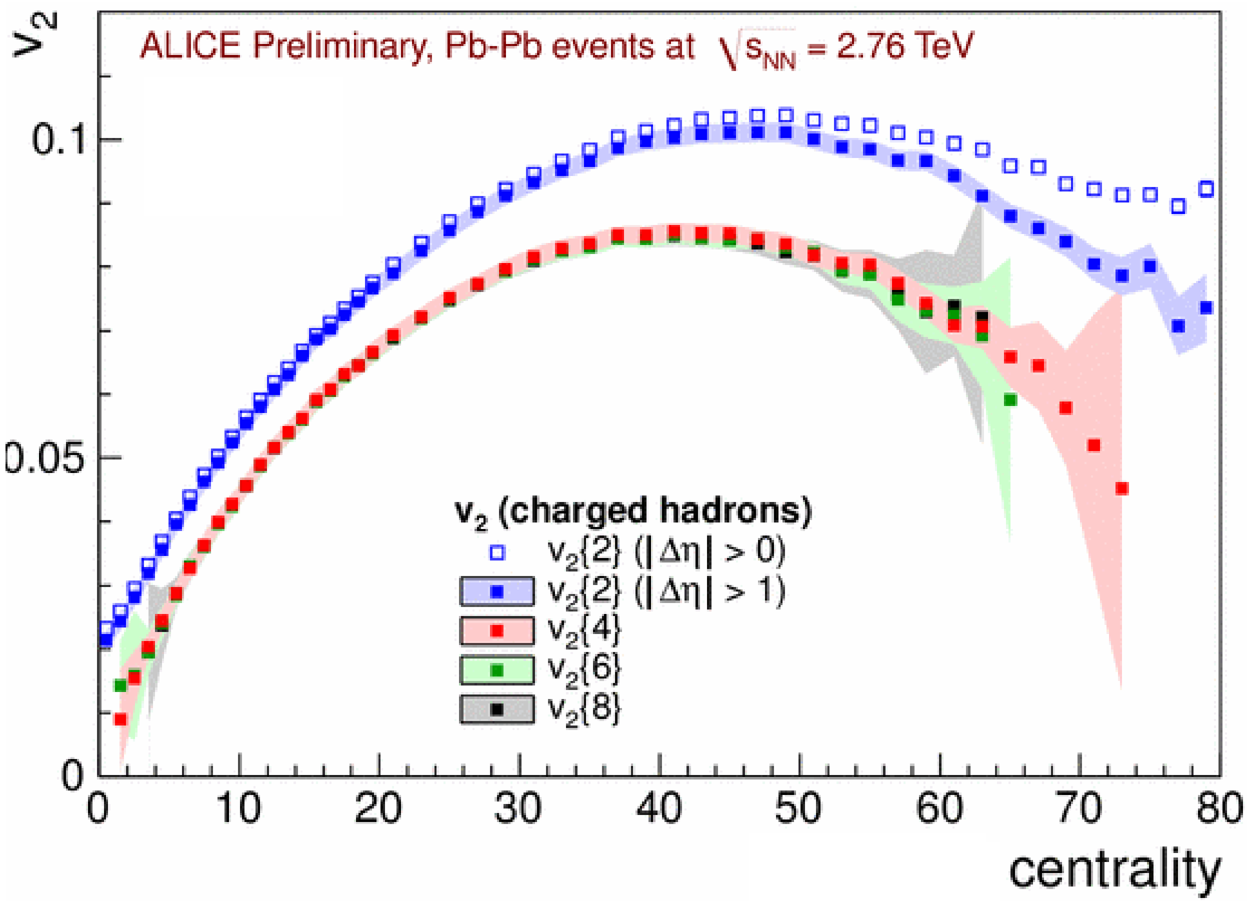
Rapidity separation between correlated particles suppress short-range non-flow:

$$v_2\{2\} > v_2\{2,|\Delta\eta|\}$$

Large non-flow in peripheral collisions

Estimating flow with multi-particle cumulants

elliptic flow vs. centrality



Rapidity separation between correlated particles suppress short-range non-flow:

$$v_2\{2\} > v_2\{2, |\Delta\eta|\}$$

Large non-flow in peripheral collisions

Note:

$v_2\{2\}$ and $v_2\{4\}$ differ not only because of non-flow, but also due to flow fluctuations (discussed later)

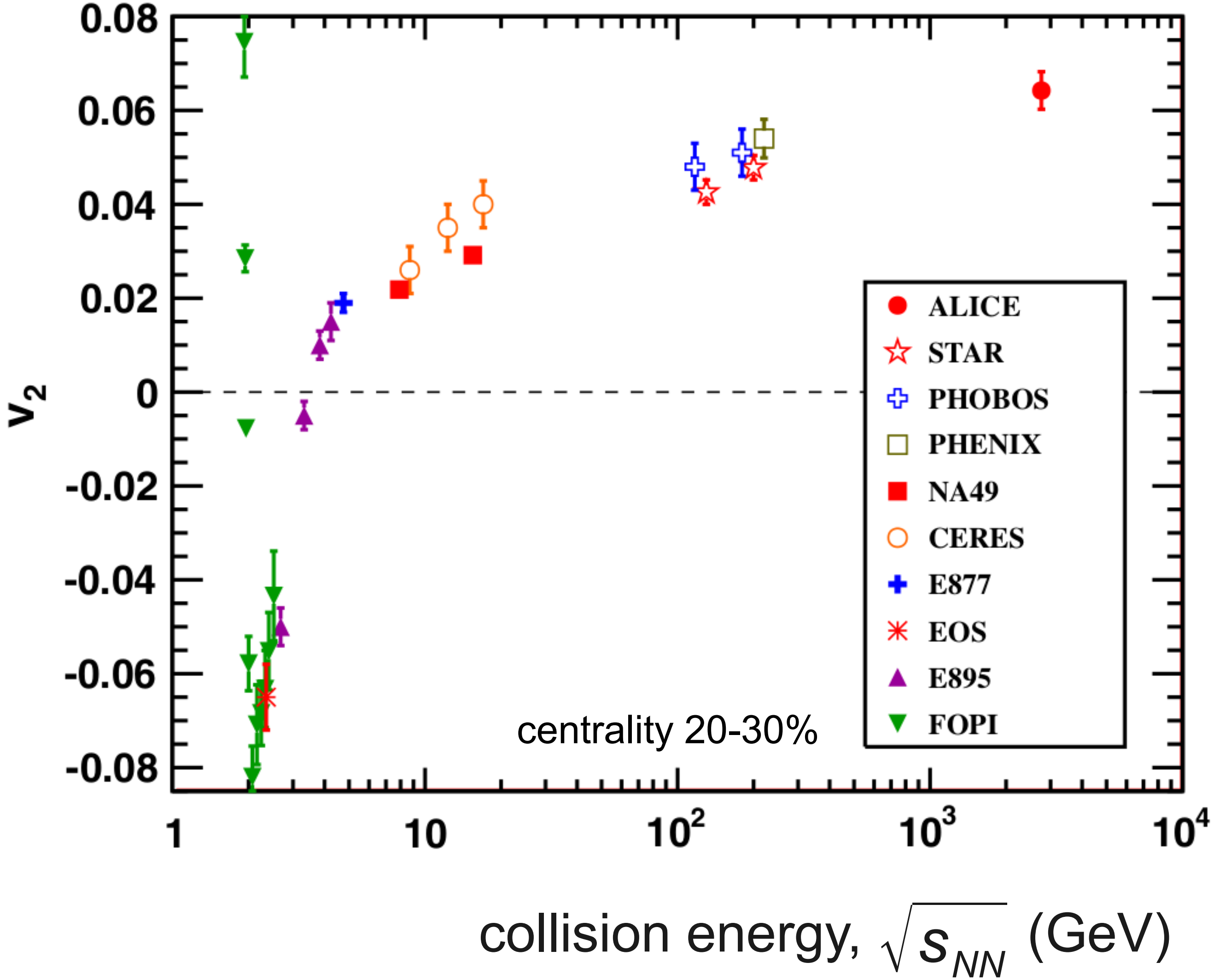
Multi-particle cumulants remove residual non-flow:

$$v_2\{4\} \approx v_2\{6\} \approx v_2\{8\}$$

Elliptic flow:

the dominant flow component at the relativistic energies

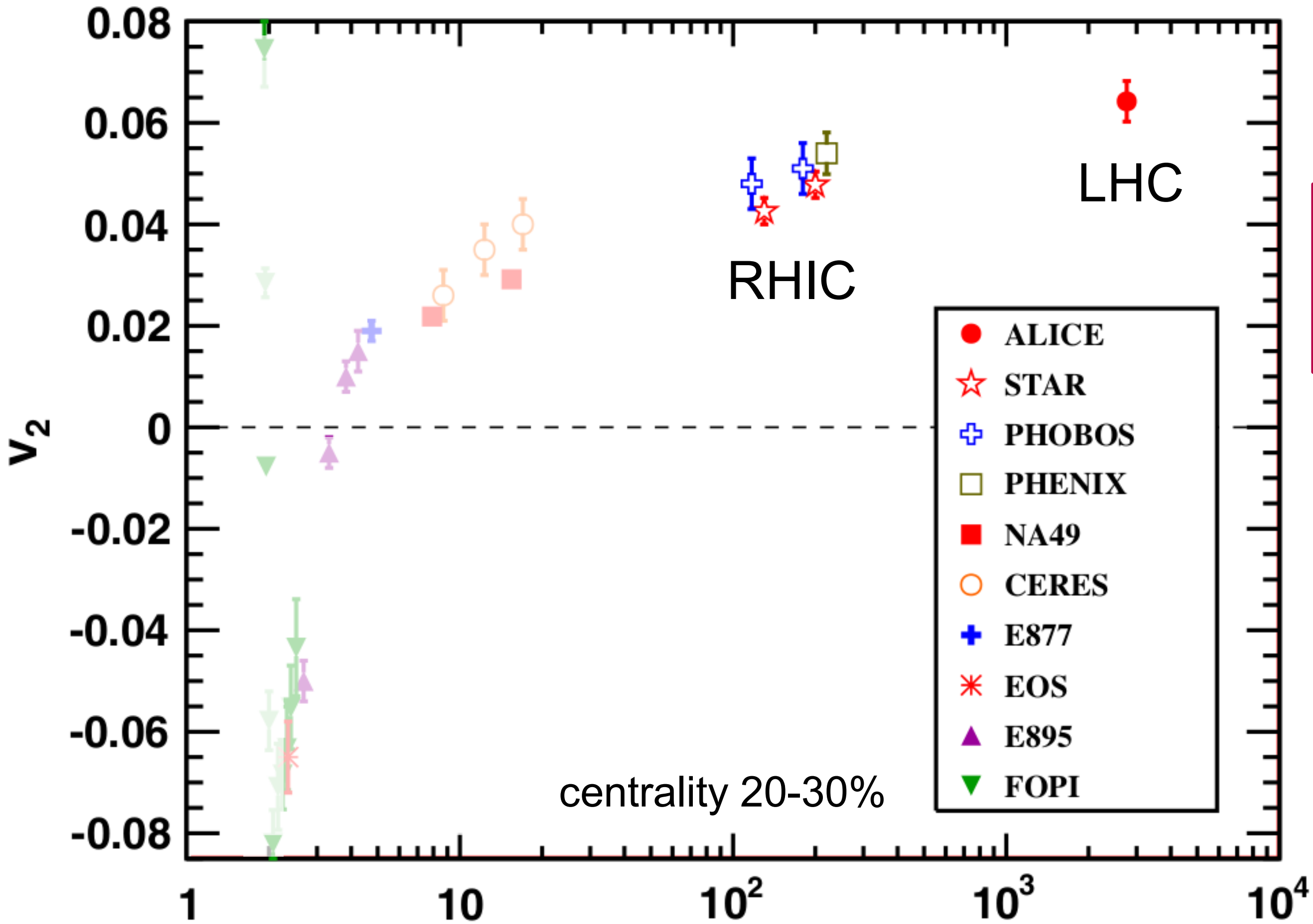
Elliptic flow vs. collision energy



Experimental results covers about 4 decades of the collision energy

Data from GSI, AGS, SPS, RHIC, and LHC experiments

Elliptic flow: RHIC vs. LHC

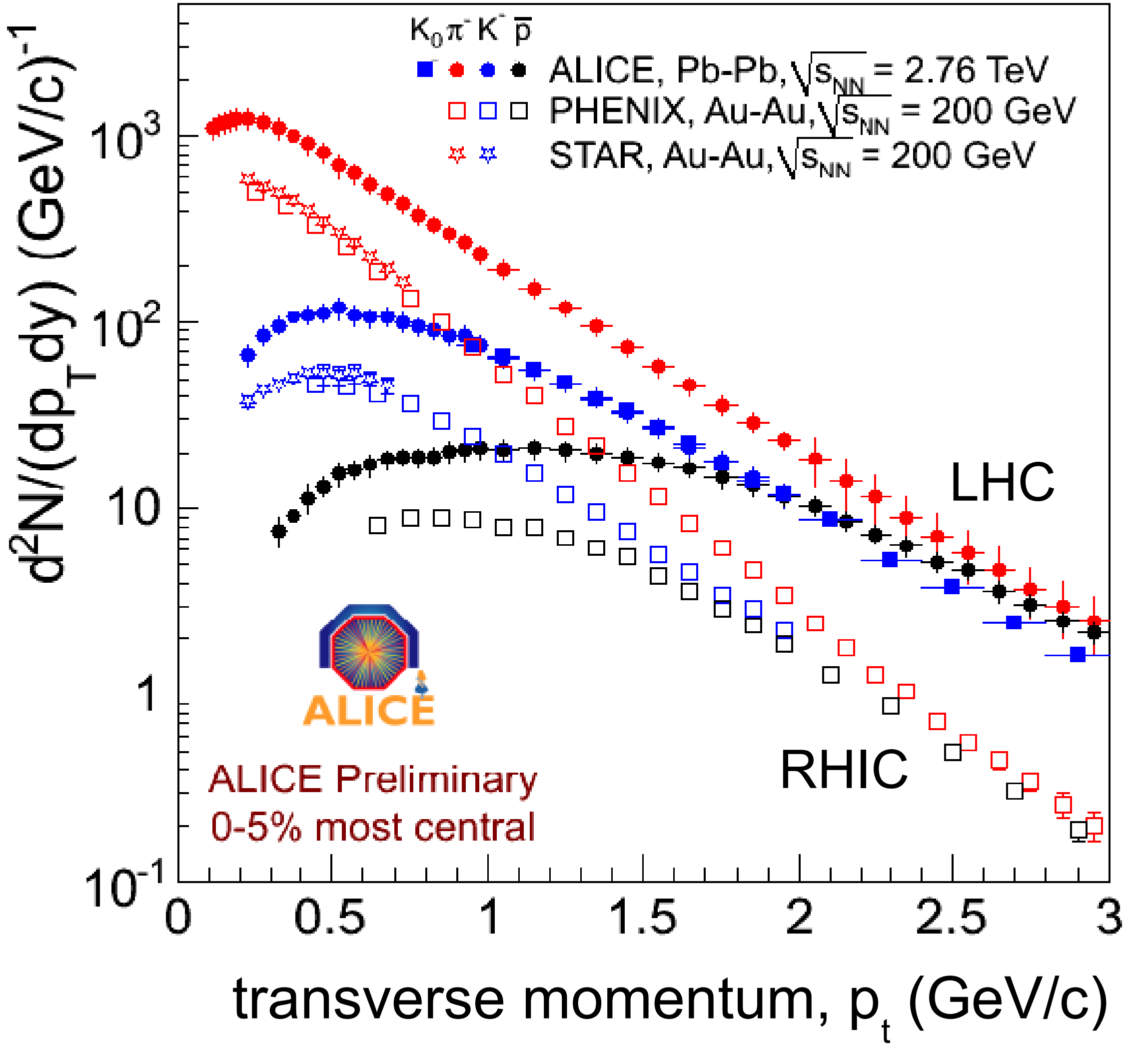


collision energy, $\sqrt{s_{NN}}$ (GeV)

30% increase of v_2 from RHIC: stronger collectivity at LHC

But: measured v_2 vs. transverse momenta has similar shape and magnitude at RHIC and LHC

Identified particle spectra: LHC vs. RHIC



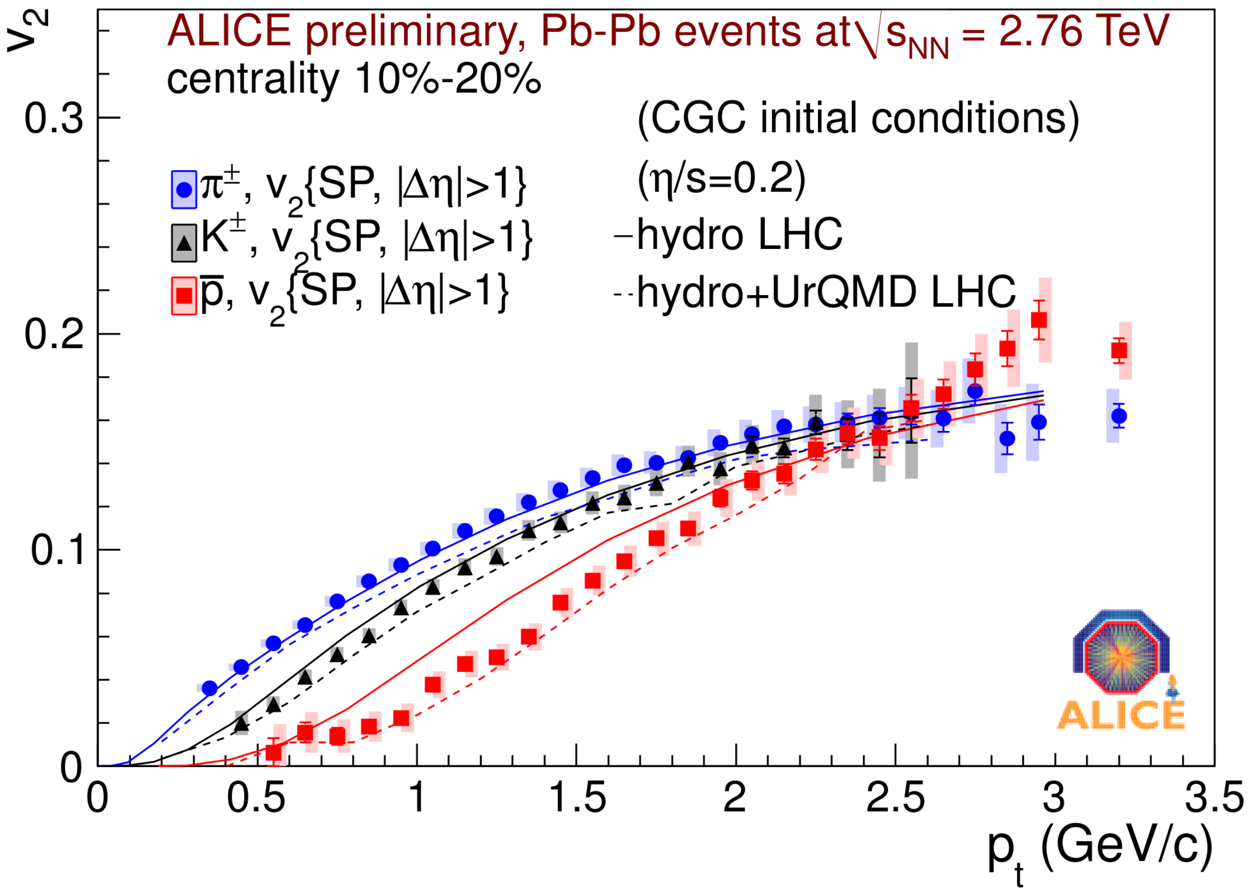
Spectra shapes changed significantly from RHIC to LHC

Radial expansion (flow):

Boost particles to higher p_t (particles gain extra radial velocity)

From Blast wave spectra fits:
20% stronger radial flow at LHC
→ increase of integral v_2

Elliptic flow mass splitting



VISHNU: Heinz et. al, arxiv:1108.5323

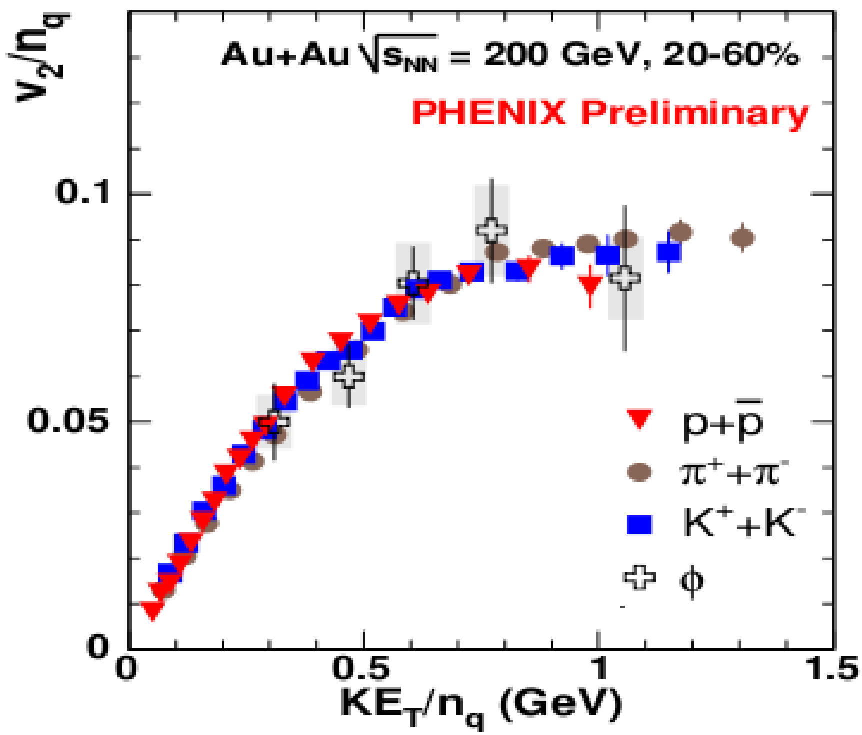
Similar to spectra:
v_2 of heavier particles
is pushed to higher p_t

Viscous hydrodynamics
well describe flow of $\pi^{\pm}$ and $K^{\pm}$:
→ sensitivity to QGP viscosity

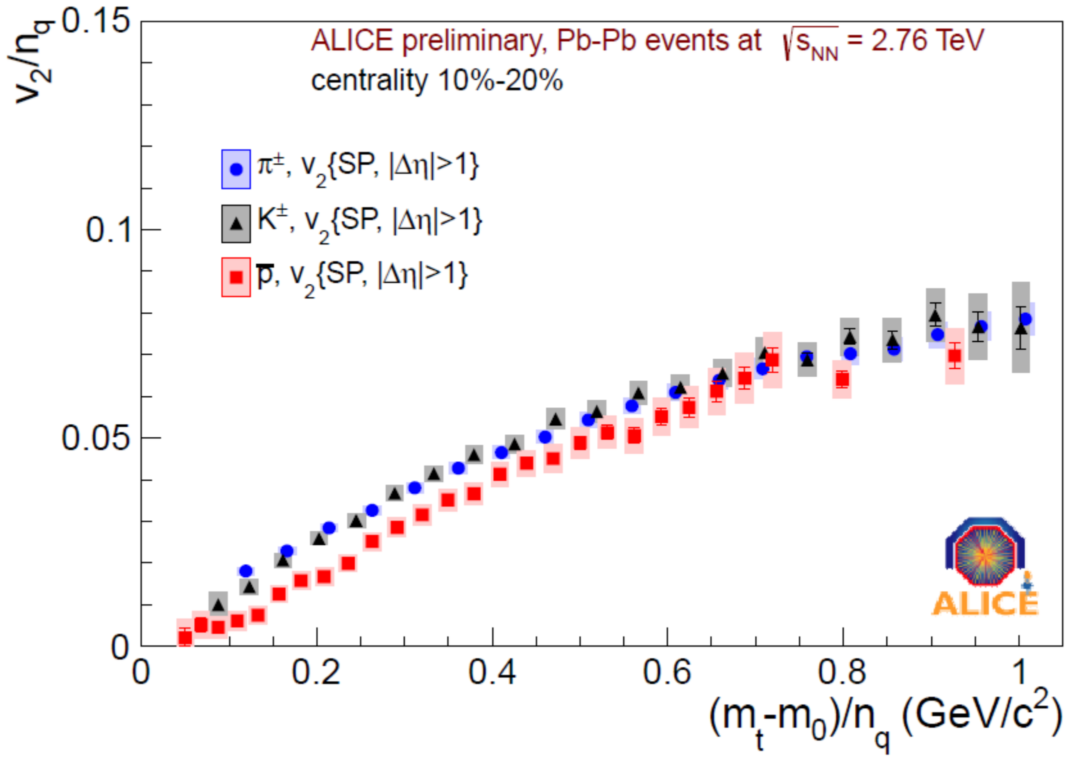
Including hadronic rescattering
with UrQMD model allows
better reproduce proton v_2:
→ sensitivity to the evolution

Constituent number of quarks scaling

RHIC



LHC



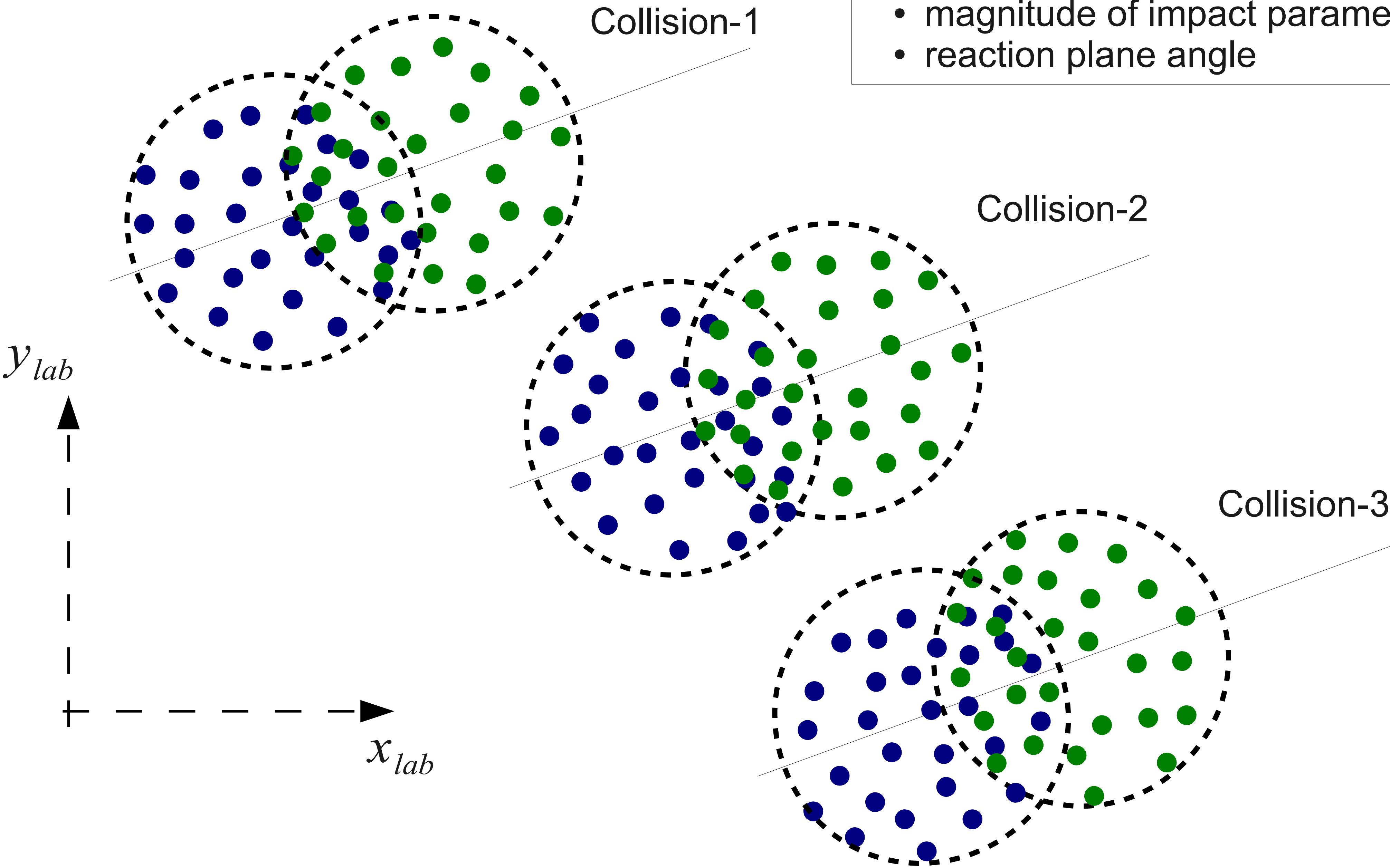
Observe approximate number of quark scaling:

Strong indication that system evolved through deconfined (QGP) phase

Flow fluctuations

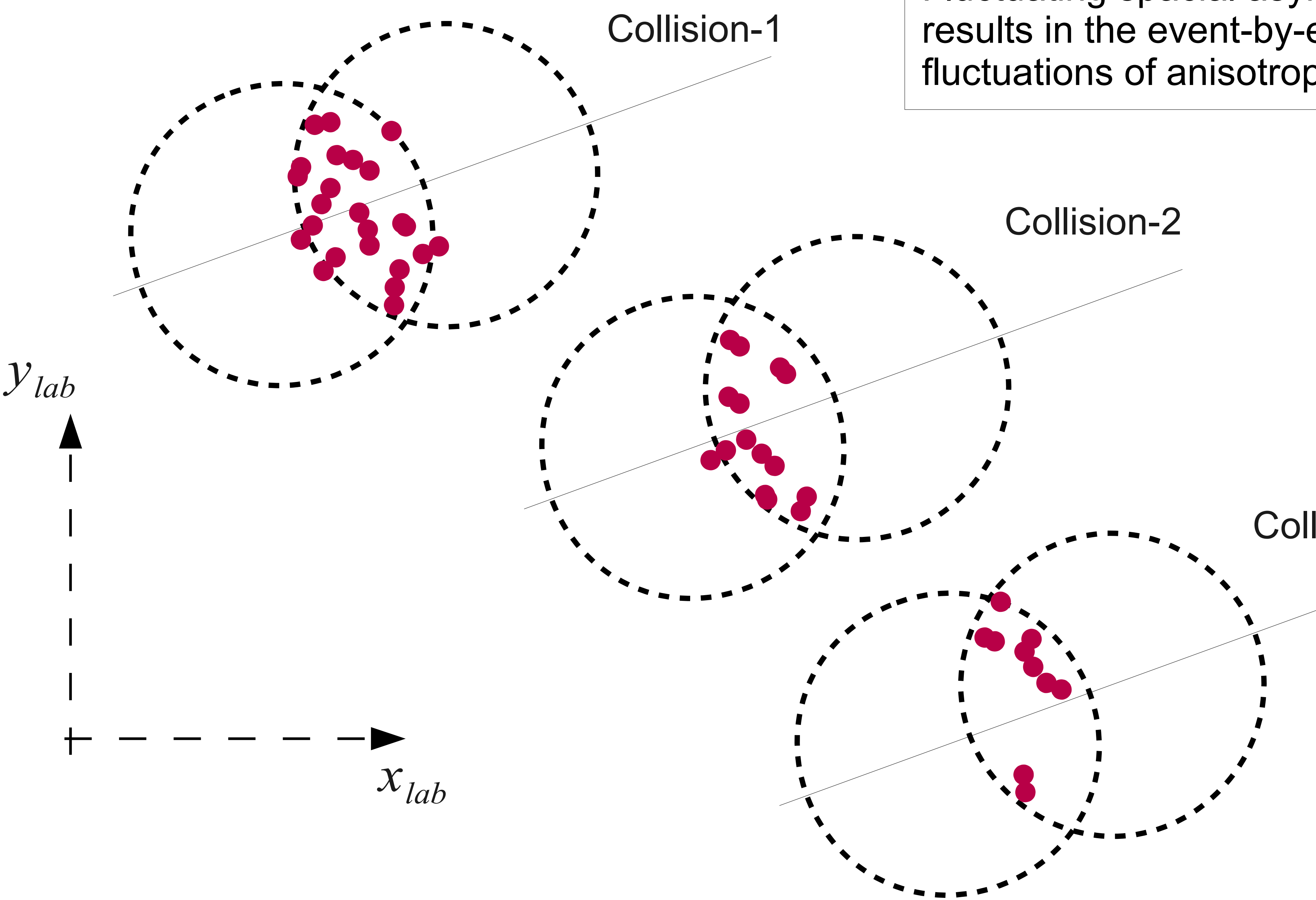
Experimentally study many collisions

Three collisions with the same:
- magnitude of impact parameter
- reaction plane angle



Fluctuating initial energy density

Fluctuating spacial asymmetry results in the event-by-event fluctuations of anisotropic flow



How fluctuations affect the measured flow?

2-particle azimuthal correlation:

$$c_n\{2\} = \langle \cos[2(\phi_i - \phi_j)] \rangle = \langle v_n^2 \rangle + \delta_{n,2}$$

$$\langle v_n^2 \rangle \neq \langle v_n \rangle^2$$

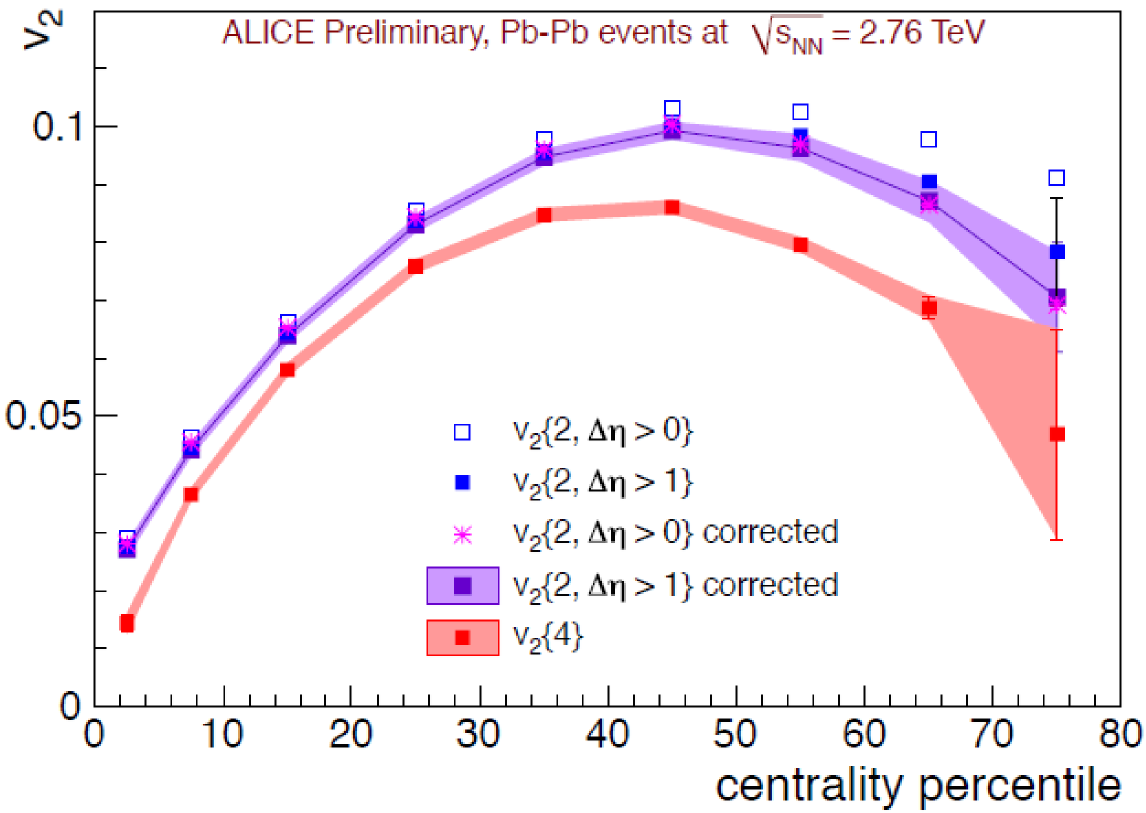
$$\langle v_n^2 \rangle = \langle v_n \rangle^2 + \sigma_n^2$$

$$\langle \cos[n(\phi_i - \phi_j)] \rangle = \langle v_n \rangle^2 + \sigma_n^2 + \delta_{n,2}$$

flow fluctuations non-flow

Elliptic flow fluctuations

2-particle correlations affected by 3 effects: $v_2\{2\} = \sqrt{\langle v_2 \rangle^2 + \sigma_2^2 + \delta_2}$



Residual non-flow subtracted based on HIJING Monte-Carlo:

$$v_2^{corr}\{2\} \approx \langle v_2 \rangle + \frac{\sigma_2^2}{2\langle v_2 \rangle}$$

Many-particle correlations free of non-flow:

$$v_2\{4\} \approx \langle v_2 \rangle - \frac{\sigma_2^2}{2\langle v_2 \rangle}$$

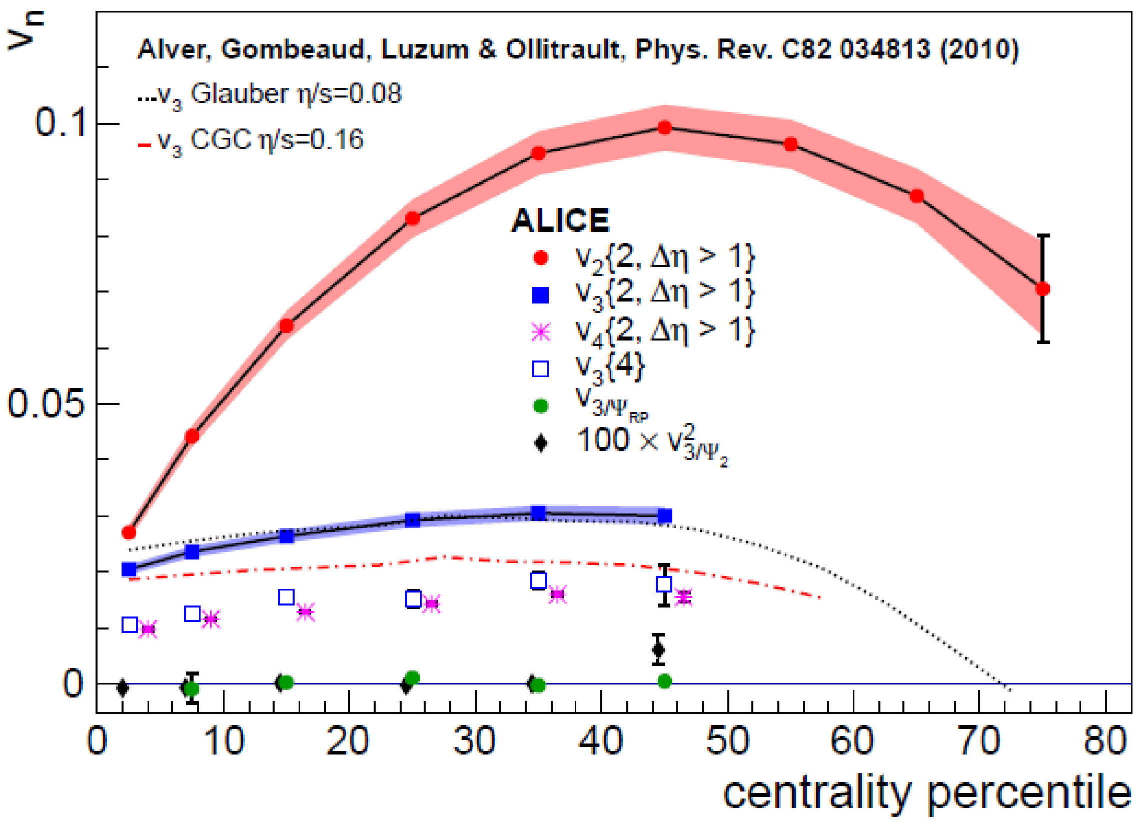
Fluctuations set the difference between $v_2^{corr}\{2\}$ and $v_2\{4\}$

Flow fluctuations are significant

Additional constraint on the initial condition

Triangular flow, v_3 - pure fluctuations

Non-zero correlations observed for $v_3^{corr}\{2\}$ and $v_3\{4\}$!



$$v_3^{corr}\{2\} = \sqrt{\langle v_3 \rangle^2 + \sigma_3^2} \neq 0$$

Due to collision symmetry the odd harmonic flow is asymmetric:

$$v_{2n+1}(-\eta) = -v_{2n+1}(\eta)$$

In the symmetric rapidity range:

$$\langle v_3 \rangle = 0$$

$$v_3^{corr}\{2\} = \sigma_3$$

Together with fluctuations in the 2nd harmonic provides strong constraints on the initial condition

Two particle azimuthal correlations:

collective flow modulations
or ridge & mach cone?

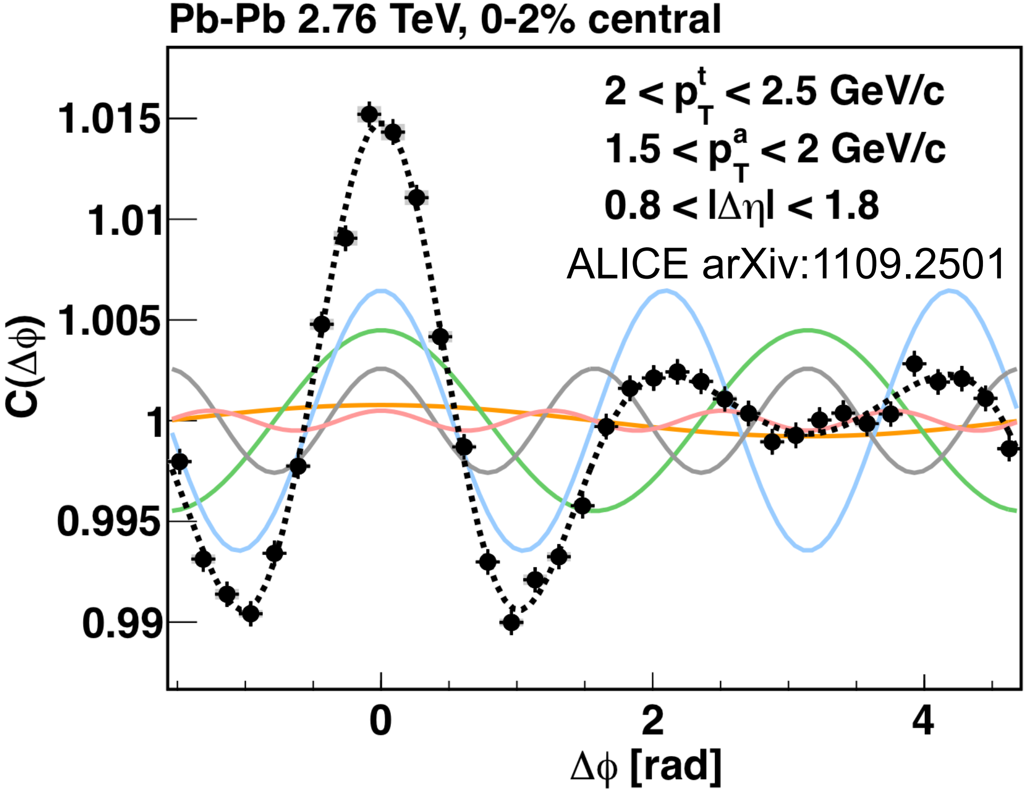
?

$$C(\phi_1 - \phi_2) \sim 1 + 2\sum_{i=1} v_{n,1} v_{n,2} \cos(n[\phi_1 - \phi_2])$$

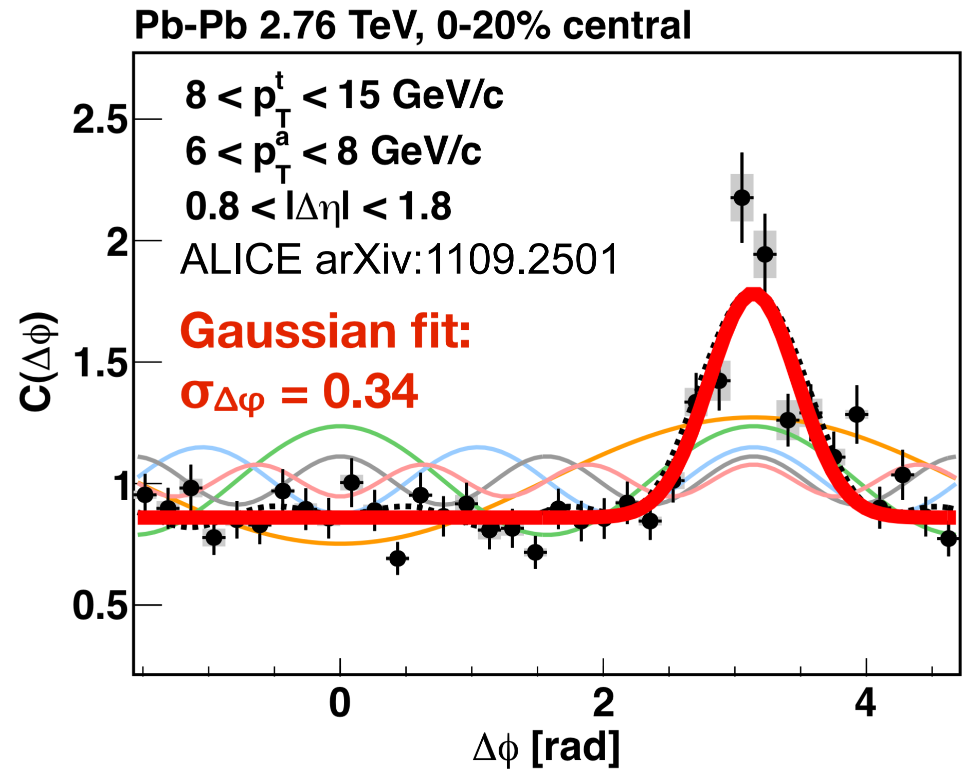
Two particle correlations and higher harmonic flow

Azimuthal correlations are studied with large rapidity gap: $0.8 < |\Delta\eta| < 1.8$

Correlations at small p_t (bulk)



Correlations at high p_t (away side jet)



"ridge" and "mach-cone" like structures are naturally described by the collective flow effects

Anisotropic flow: summary

- Anisotropic transverse flow is an important experimental observable to study the evolution of a heavy-ion collision and understand the properties of the quark-gluon plasma (QGP).

- It provides constraints on:

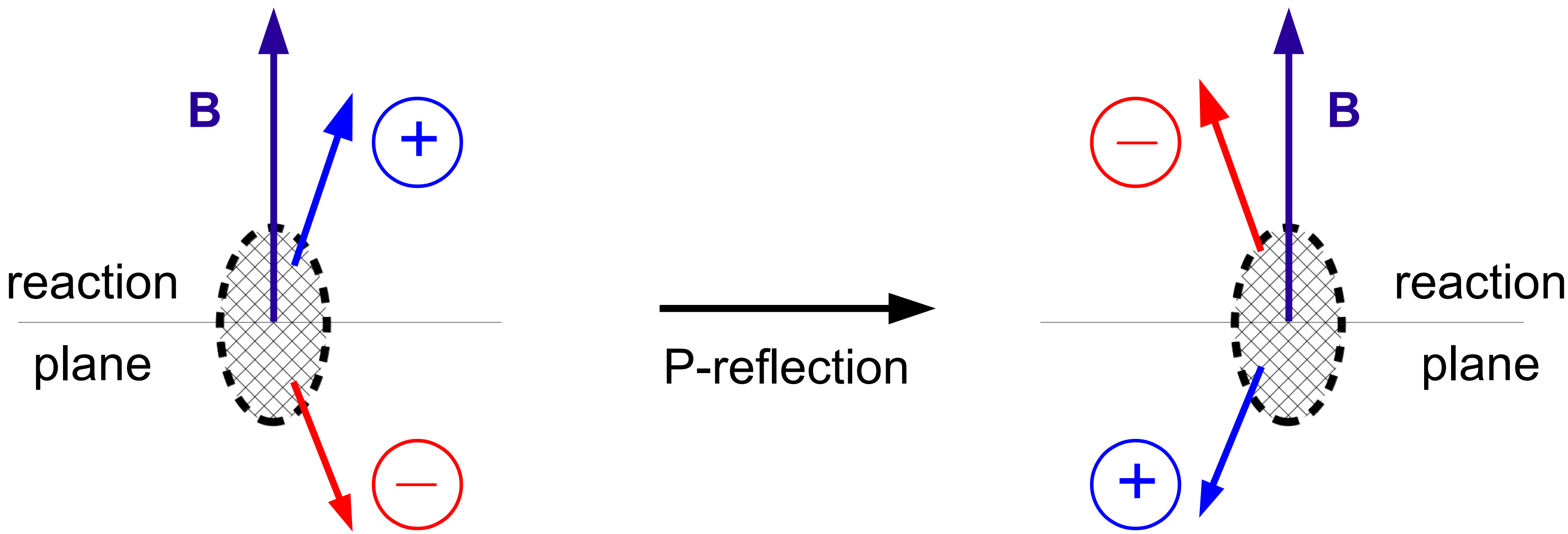
  - ✔ Equation of state of the created matter
  - ✔ Transport properties (i.e. viscosity) of the QGP matter
  - ✔ Shape of the initial conditions in a heavy-ion collision

- Helps to understand the origin of the correlations between produced particle

Probes of local parity violation in strong interactions

$$\frac{dN_{\pm}}{d(\Delta\phi_{\pm})} \sim 1 + 2\,a_{\pm} \sin\Delta\phi_{\pm}$$

Charge asymmetry wrt. the reaction plane



Coordinate/momentum are vectors:

$$\vec{r} \rightarrow -\vec{r} \qquad \vec{p} \rightarrow -\vec{p}$$

Magnetic field (**B**) is axial-vector:

$$\vec{B} \rightarrow \vec{B}$$

Charge asymmetry wrt. the Ψ_{RP} breaks the parity symmetry

Theoretical motivation for the local parity violation:

T.D. Lee, PRD8:1226 (1973)
Morley, Schmidt, Z.Phys.C26:627 (1985)
Kharzeev, et.al, PRL81:512 (1998)
Kharzeev, et.al, PRD61:111901 (2000)
Voloshin, PRC62:044901 (2000)
Kharzeev, et. al. PLB545:298 (2002)
Finch, Chikanian, Longacre, Sandweiss, Thomas, PRC65:014908(2002)

Observable to probe local parity violation

- Asymmetry fluctuates event by event. P-odd observable yields zero (no global violation of the symmetry):

$$\langle a_{\pm} \rangle = \langle \sin(\phi_{\pm} - \Psi_{RP}) \rangle = 0$$

- Study P-even correlations: $<a_\alpha a_\beta>$ $(\alpha, \beta = \pm)$
  Measure the difference between **in-plane** and **out-of-plane** correlations:

$$\langle \cos(\phi_\alpha + \phi_\beta - 2\Psi_{RP}) \rangle = \langle \cos\Delta\phi_\alpha \cos\Delta\phi_\beta \rangle - \langle \sin\Delta\phi_\alpha \sin\Delta\phi_\beta \rangle =$$

Voloshin PRC70:057901 (2004)

$$= [\langle v_{1,\alpha} v_{1,\beta} \rangle + Bg^{(in)}] - [\langle a_\alpha a_\beta \rangle + Bg^{(out)}]$$

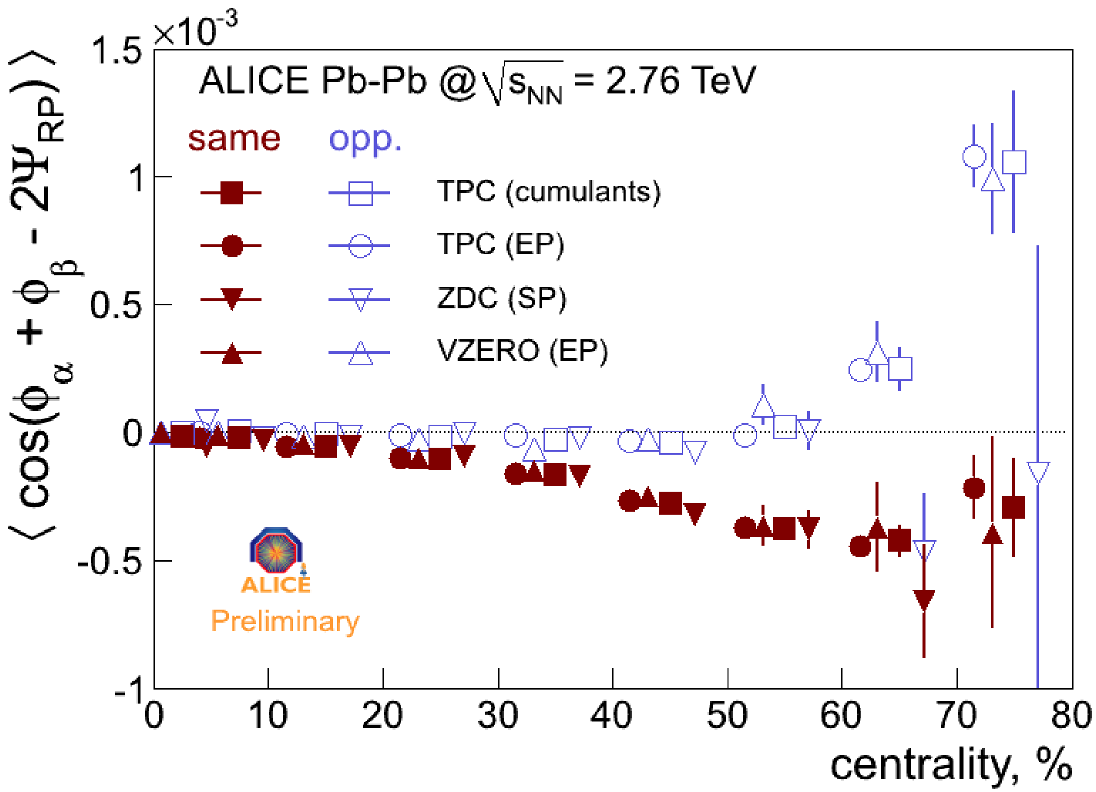
$$\Delta\phi_{\alpha,\beta} = \phi_{\alpha,\beta} - \Psi_{RP}$$

- Large RP-independent background correlations cancel out in $Bg^{(in)}$ - $Bg^{(out)}$

  $Bg^{(in)}$ ($Bg^{(out)}$) denotes in- (out-of) plane background correlations

- RP-dependent (P-even) backgrounds contribute:
  → $Bg^{(in)}$ - $Bg^{(out)}$ term
  → $<v_{1,\alpha} v_{1,\beta}>$: directed flow (zero in symmetric rapidity range) + flow fluctuations

Charge separation in Pb-Pb collisions at LHC



3-particle correlations measured with the reaction plane estimated from:

- Charge particle reconstructed with TPC
  - ✓ Cumulants and mixed harmonics
- Particles counted with VZERO detectors
- Spectator deflection measured by ZDCs

Observe negative **same** sign and small/positive **opposite** sign correlations

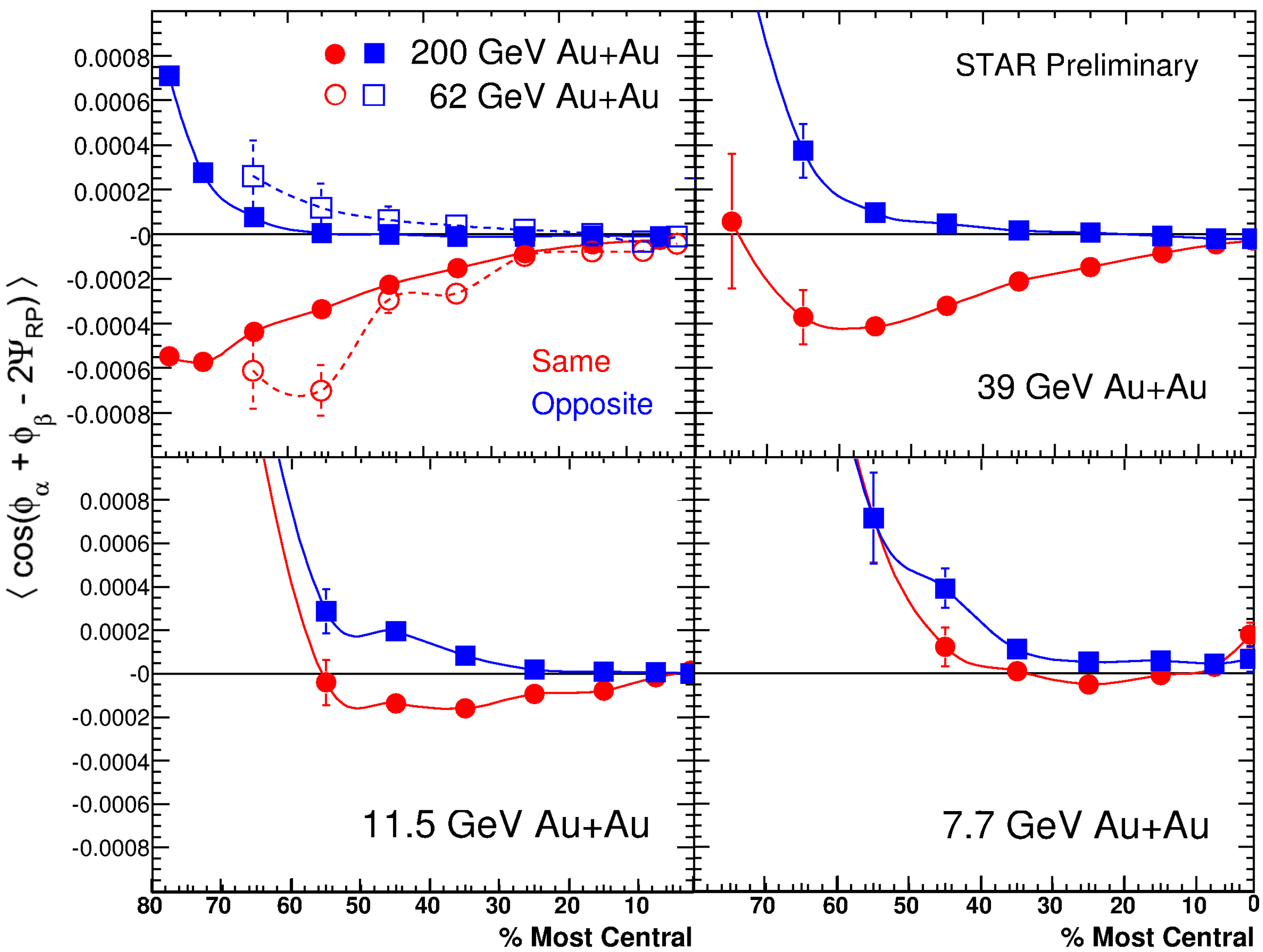
- Very good agreement between results with different estimates of the reaction plane:

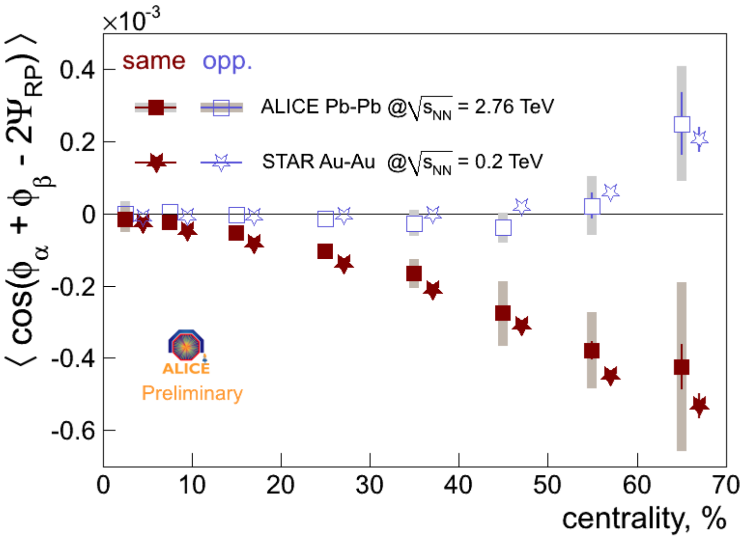
  → evidence for correlations wrt. to the reaction plane

- Charge separation observed in Pb-Pb collisions at $\sqrt{s_{NN}}$ = 2.76 TeV

Comparison with RHIC results

STAR results: D. Gangadharan (QM2011)

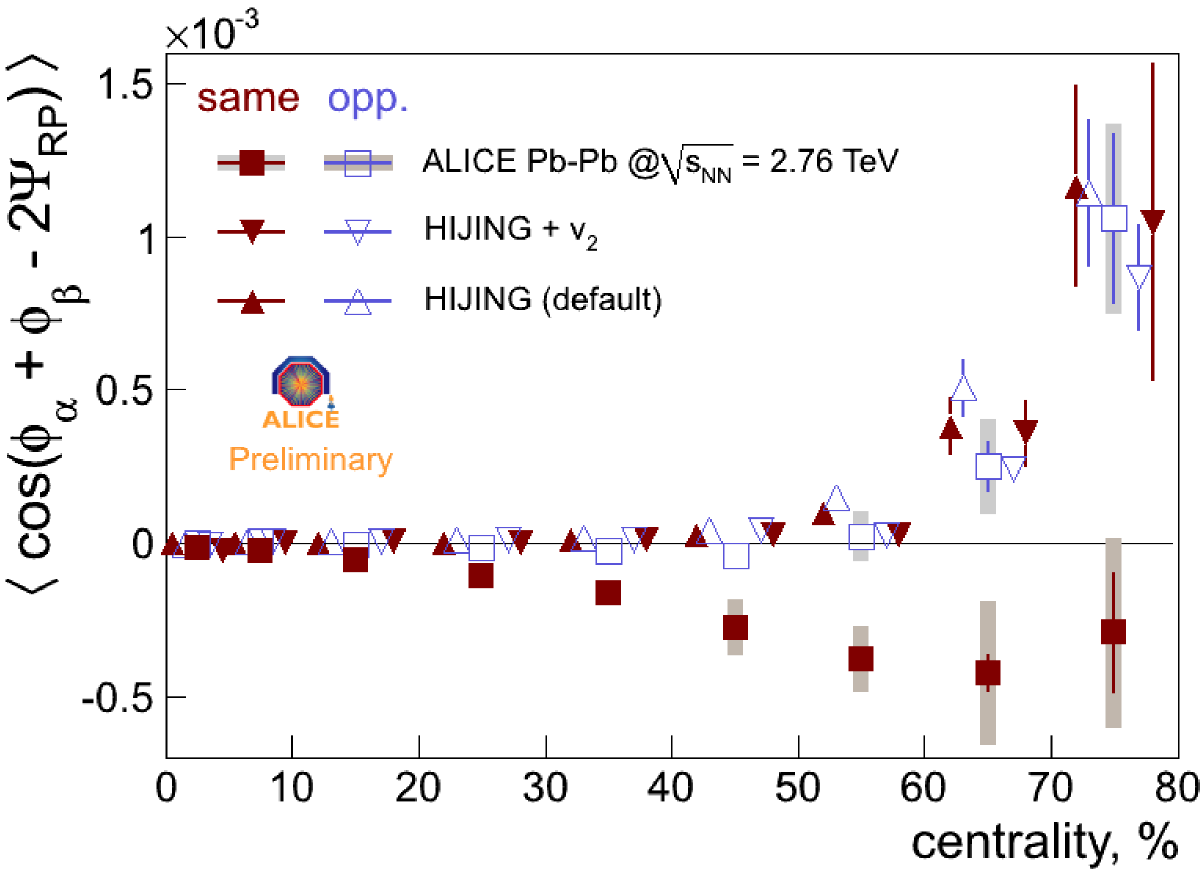




Note: RHIC data plotted inversely vs. centrality than the LHC data

- RHIC and LHC observe charge separation
- Separation seems to disappear between 11.5 and 7.7 GeV energies

Comparison with HIJING Monte-Carlo



HIJING reproduces the trends seen for opposite sign correlations

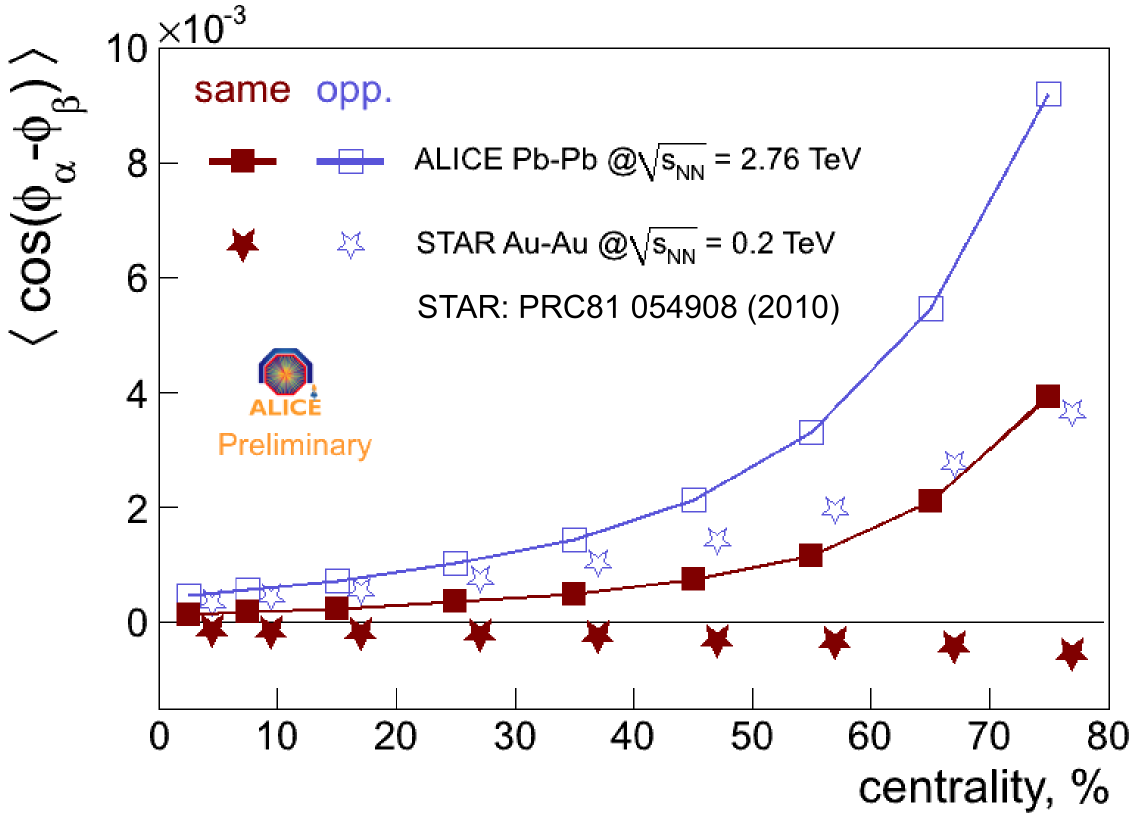
Similar correlations for opposite and same sign pairs in HIJING

Little/no charge dependence in HIJING

Other sources of background correlations:

- Flow fluctuations: D. Teaney & L. Yan, PRC 83, 064904 (2011)
- Charge conservation: S. Pratt, arXiv:1002.1758 [nucl-th]

Constraining backgrounds with two particle correlations



Similarity to RHIC:

- correlation strength between opposite sign pairs is larger than the same sign correlation

Difference from RHIC:

- Positive same sign correlation at LHC (while negative at RHIC)
- Magnitude of correlations is large than at RHIC

$$\langle \cos(\phi_\alpha - \phi_\beta) \rangle = \langle \cos\Delta\phi_\alpha \cos\Delta\phi_\beta \rangle + \langle \sin\Delta\phi_\alpha \sin\Delta\phi_\beta \rangle =$$

$$= [\langle v_{1,\alpha} v_{1,\beta} \rangle + Bg^{(in)}] + [\langle a_\alpha a_\beta \rangle + Bg^{(out)}]$$

Significant change in the correlation pattern for 2-particle correlations from RHIC to LHC

Summary

Anisotropic transverse flow is an important experimental observable to study the evolution of a heavy-ion collision and understand the properties of the quark-gluon plasma (QGP).

- It provides constraints on:
  - ✓ Equation of state of the created matter
  - ✓ Transport properties (i.e. viscosity) of the QGP matter
  - ✓ Shape of the initial conditions in a heavy-ion collision
- Helps to understand the origin of the correlations between produced particle

Charge dependent azimuthal correlations are observed at RHIC and LHC:

- Correlations reflect collective effect
- Magnitude of the correlations is similar to that at RHIC energies
- Observe different behavior for the first harmonic two particle azimuthal correlations than at RHIC