# Study of flow phenomena in heavy-ion collisions

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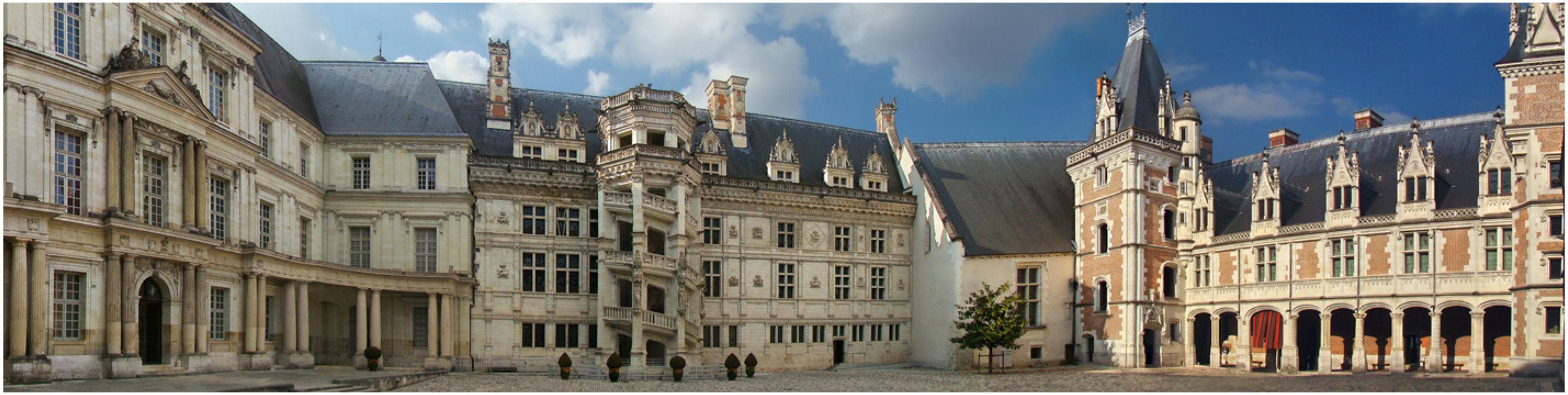
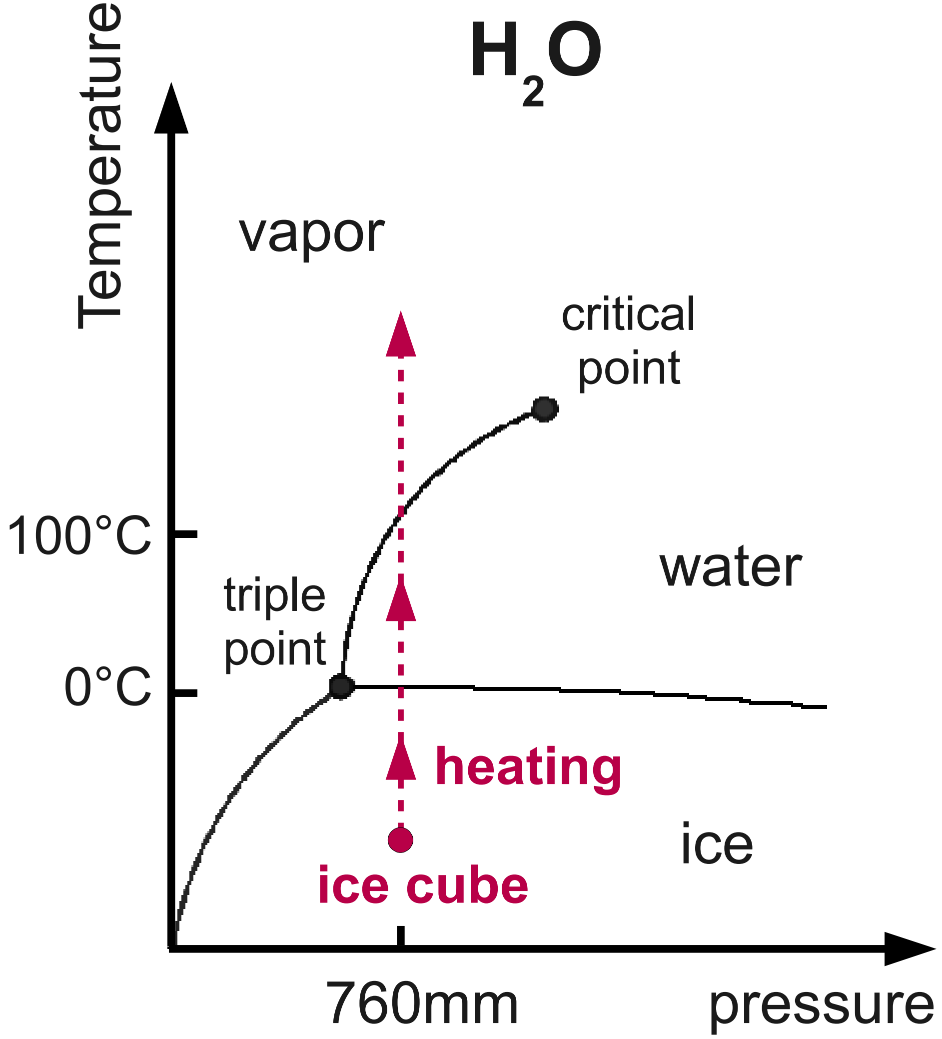
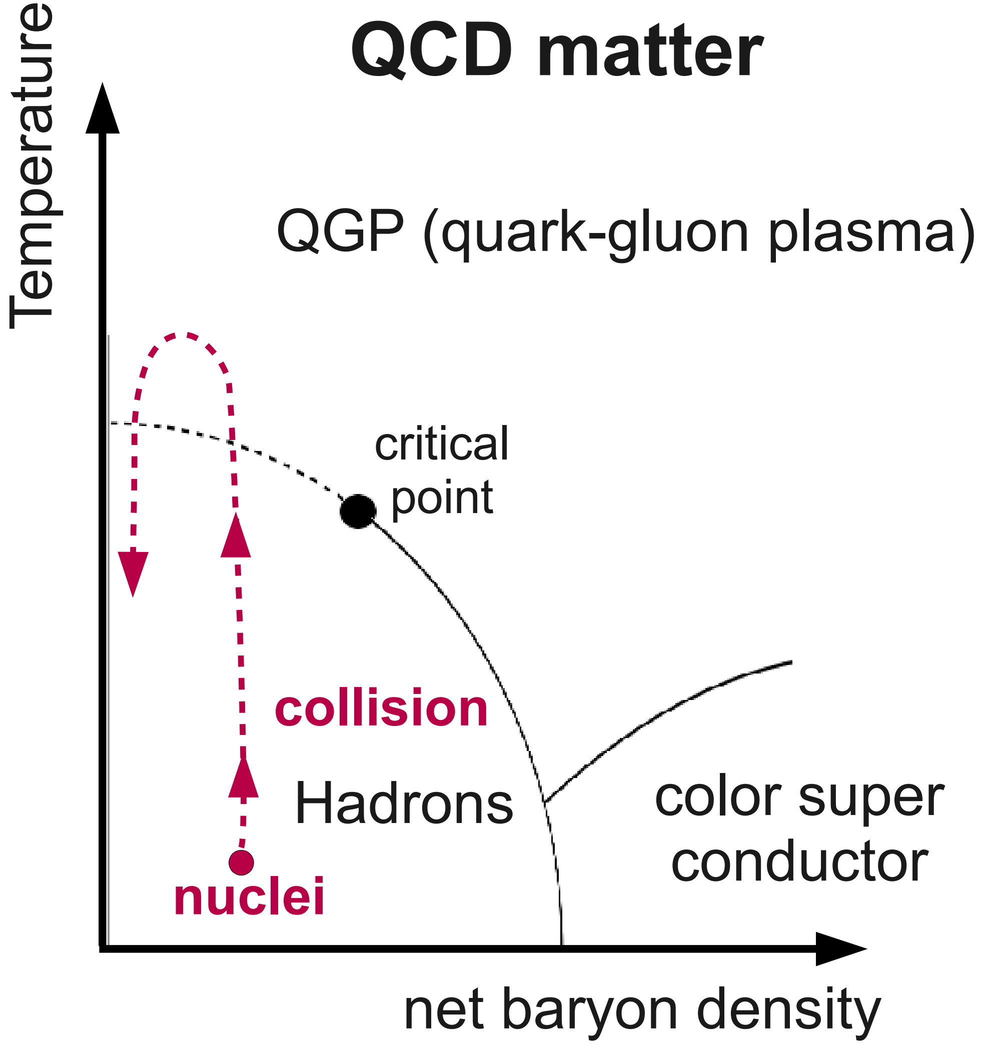


24th Rencontres de Blois, France

May 31, 2012

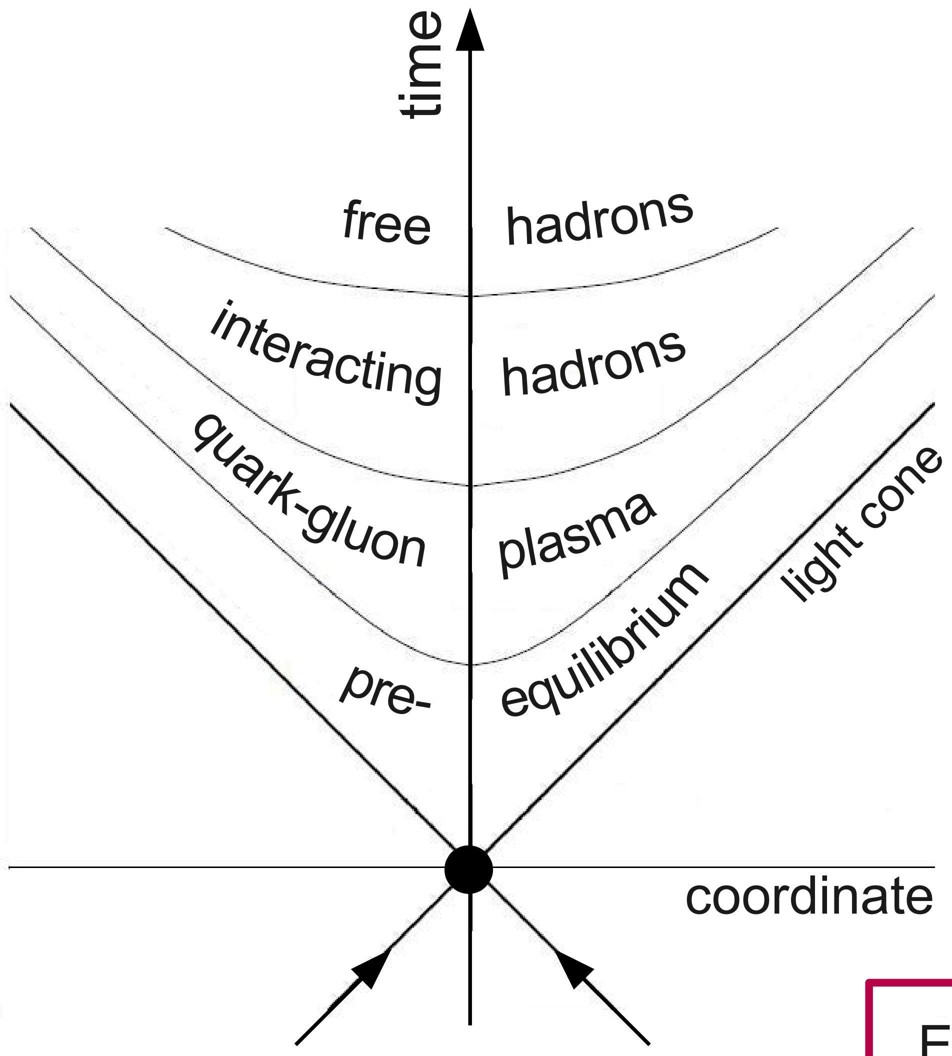
# Experimental study of the phase diagram





Experimental study of QGP phase diagram by:
smashing nuclei in head-on collision and
converting cold nuclear matter into a fireball of partons

# Evolution of the system created in HIC



Nuclei just before collision

- Initial pre-equilibrium state

  hard parton scattering & jet production
  gluonic fields (Color Glass Condensate)

- Quark-gluon plasma formation

  thermalization (hydrodynamics)

- QGP expansion and decay

  phase transition of partons into hadrons

  - Hadronization
  - Rescattering & chemical freeze out
  - Kinetic freeze out (stop interacting)

Experimentally observe only hadronic state

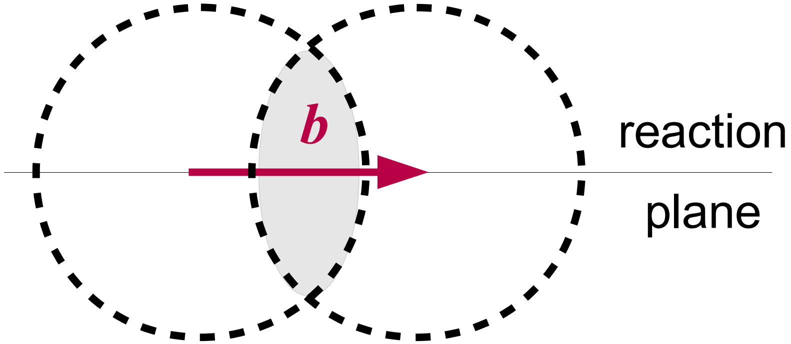
Many observables need to be studied
to establish the properties of QGP

# Anisotropic transverse flow in a heavy-ion collisions

- 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

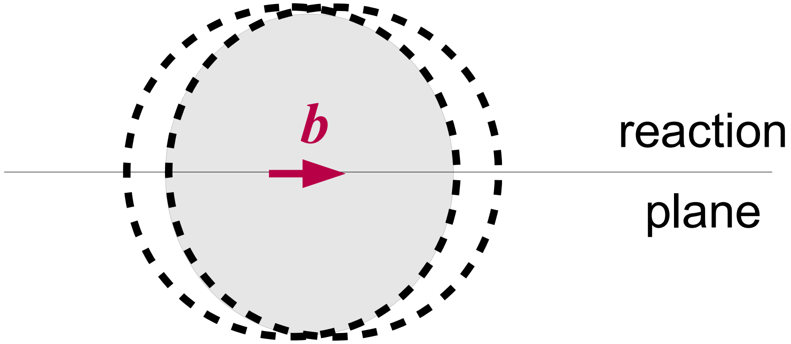
# Colliding nuclei has a finite size

Peripheral collision (large $b$)



Overlap region is strongly asymmetric in the transverse plane

Central collision (small $b$)



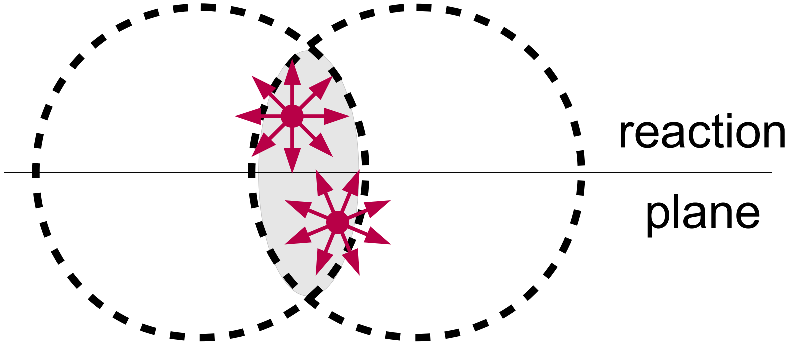
Overlap region is close to be symmetric in the transverse plane

Asymmetry of the overlap region depends on the impact parameter

$b$ - impact parameter

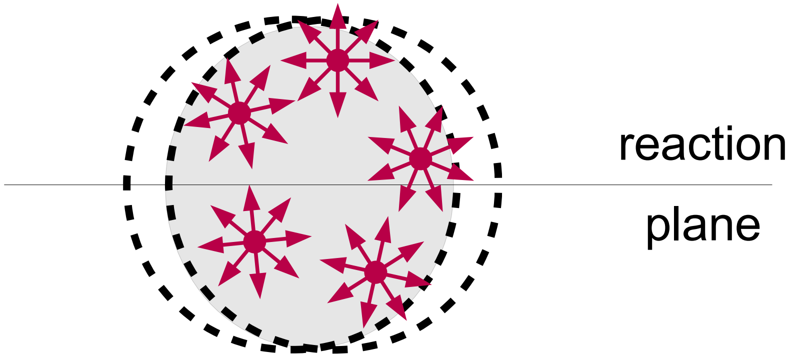
# Nucleon-nucleon collisions in the overlap region

Peripheral collision



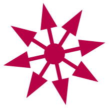
Small number of nucleon-nucleon collisions:
few particles produced

Central collision



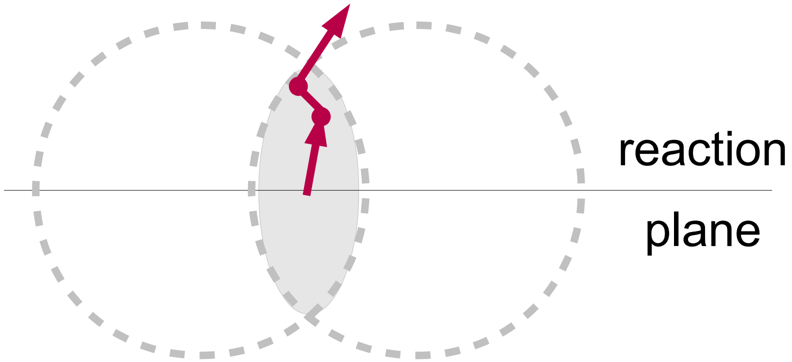
Large number of NN collisions:
abundant particle production

Number of produced particles
is correlated with the impact parameter


- elementary
nucleon-nucleon (NN) collision

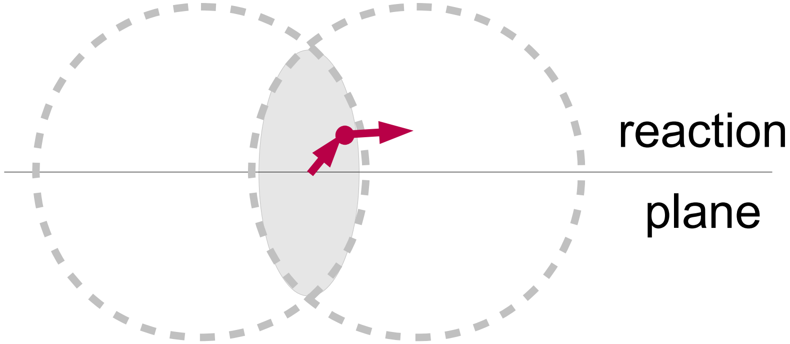
# Produced particles interact with each other

Particle emitted out-of-plane



Multiple interaction with medium

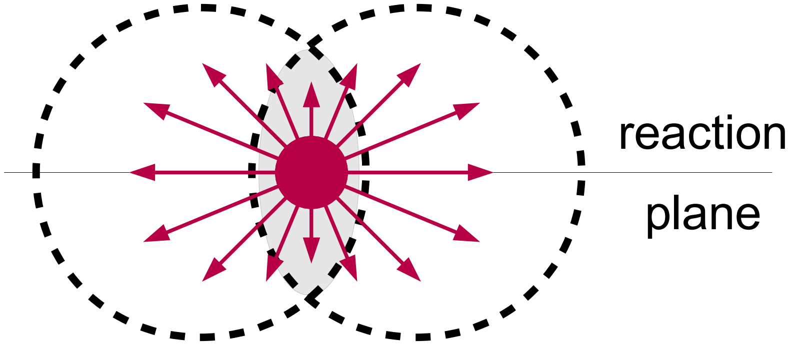
Emitted in-plane



Less interaction - small modification

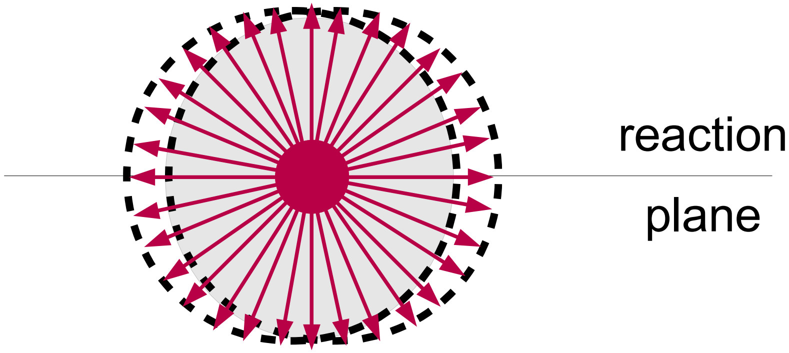
# Particle collectivity

Peripheral collision



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

Central collision

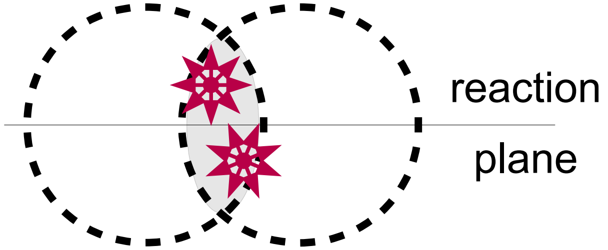


Multiple interaction with medium but small initial spacial asymmetry:
small asymmetry in the momentum space

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

# Quantifying azimuthal asymmetry

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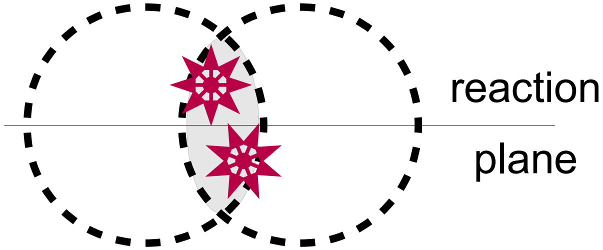

$x, y$ - position of each elementary NN interaction

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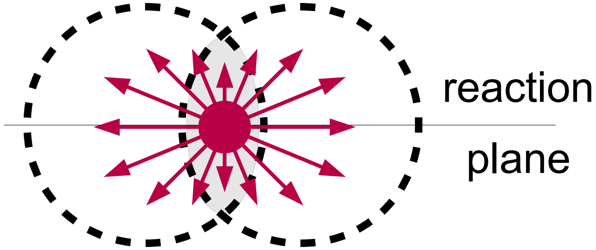
Momentum space asymmetry:

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



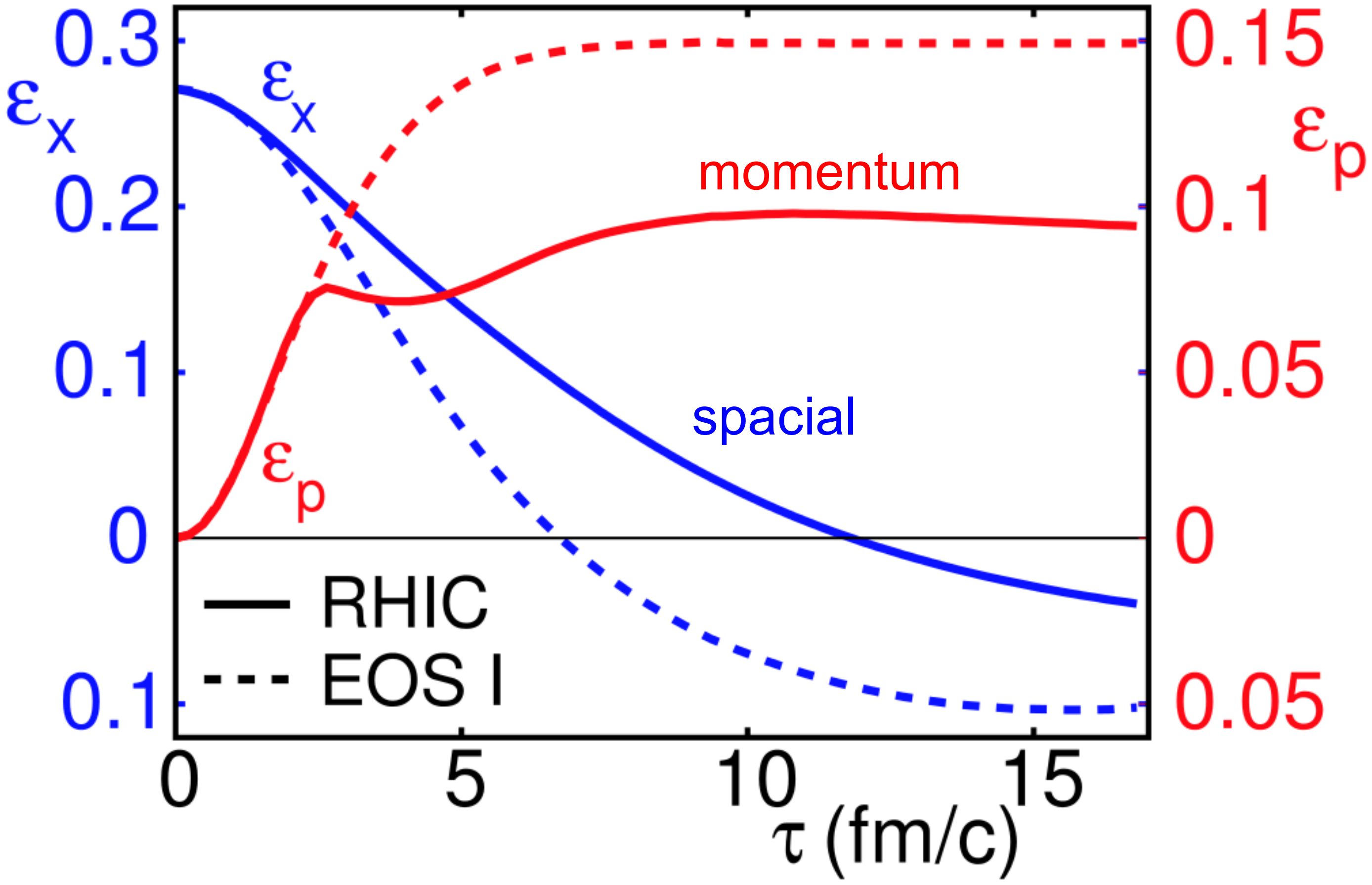
Second Fourier harmonic in momentum space

$p_t$ - particle transverse momentum

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

# Time evolution of the spacial and momentum asymmetries

arXiv:0901.4355



Spacial asymmetry drops very fast

Momentum asymmetry develops very early

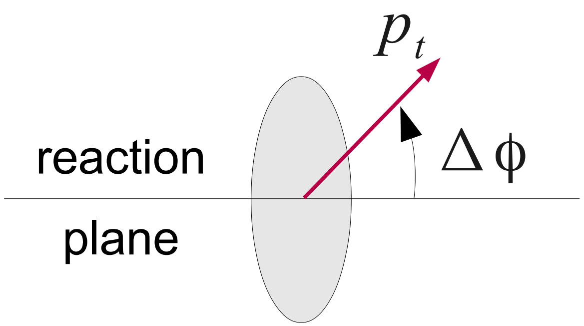
EoS I: massless ideal gas
EoS RHIC: matching Lattice QCD

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

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

$v_1$ - directed flow

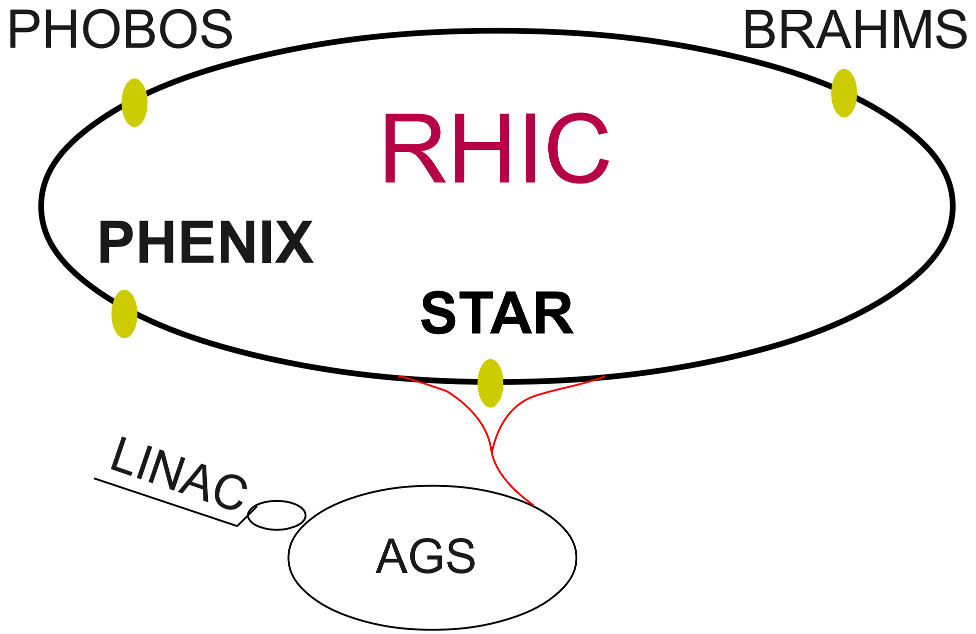
$v_2$ - elliptic flow

$v_3$ - triangular flow

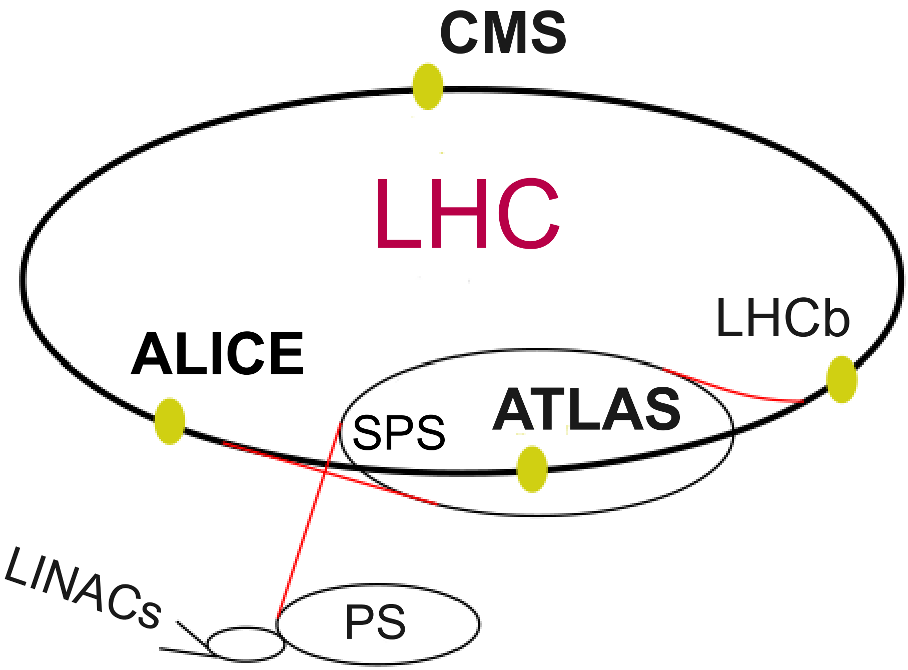
# Experimental measurements of the anisotropic flow

# Modern ultra-relativistic HI colliders

## Relativistic Heavy Ion Collider



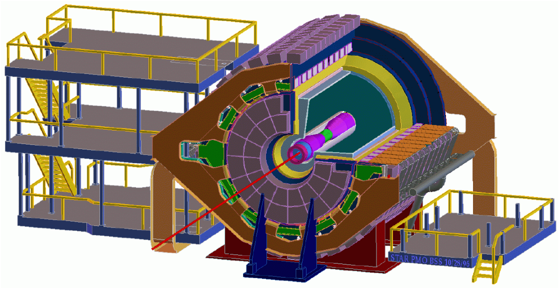
## Large Hadron Collider



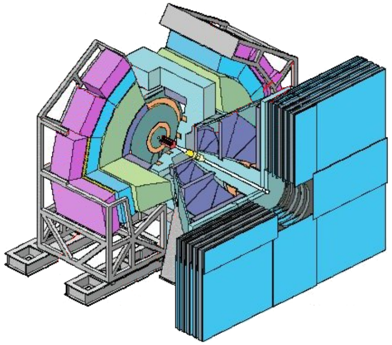
| | **RHIC** | **LHC** |
|---|---|---|
| Location | BNL (USA) | CERN (Europe) |
| Circumference | 3.8 km | 27 km |
| Species | p, d, Cu, Au, U<br>polarized protons | p, Pb |
| Center of mass energy per nucleon pair | in GeV<br>7.7-38, 62, 200<br>500 (pp only) | in TeV<br>0.9, 2.76, 7 (pp)<br>2.76 (Pb)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

# Current heavy-ion experiments at RHIC and LHC

**STAR** (Solenoidal Tracker At RHIC)



**PHENIX** (Pioneering High Energy Nuclear Ion Experiment)

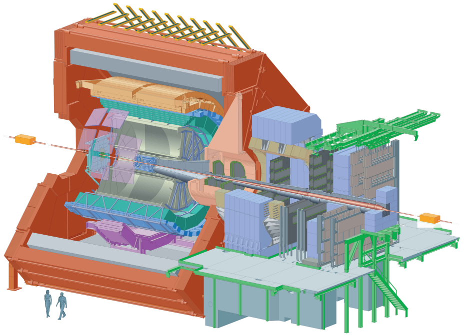


**Main capabilities for heavy-ion studies**:

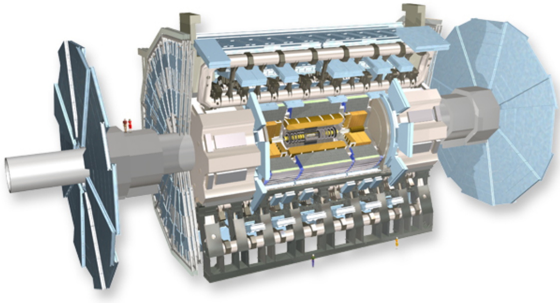
Charge particle tracking and identification:
full azimuth, large rapidity coverage
wide $p_t$ range: ~ 100 MeV/c to ~ 100 GeV/c

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

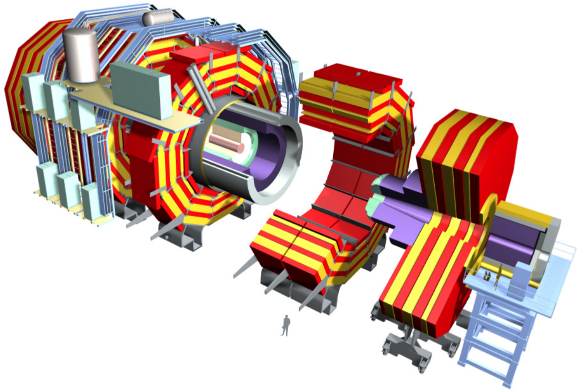
**ALICE** (A Large Ion Collider Experiment)



**ATLAS** (A Toroidal LHC Apparatus)



**CMS** (Compact Muon Solenoid)



# Anisotropic flow measurement techniques

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

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

- 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

# Non-flow correlations

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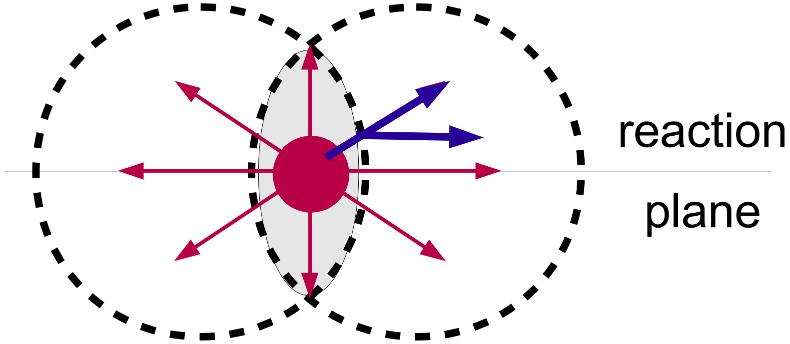
Example: 2-particle decay



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:

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

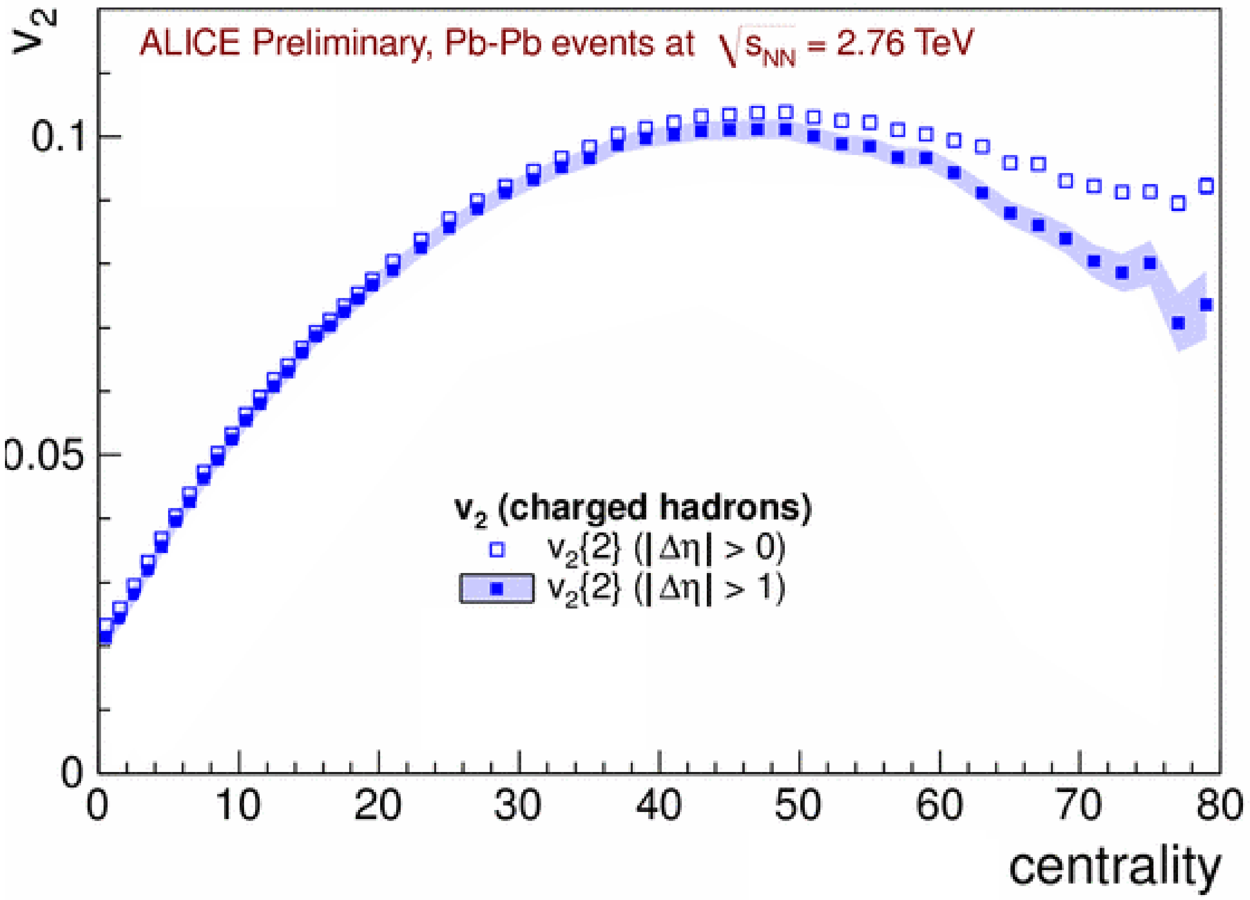
Collective flow:
correlations between particles through the common plane of symmetry

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

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

# Estimating flow with multi-particle cumulants

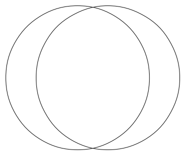
elliptic flow vs. centrality



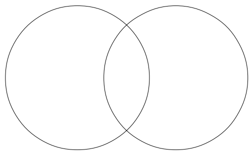
Rapidity separation between correlated particles suppress short-range non-flow:

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

Large non-flow in peripheral collisions



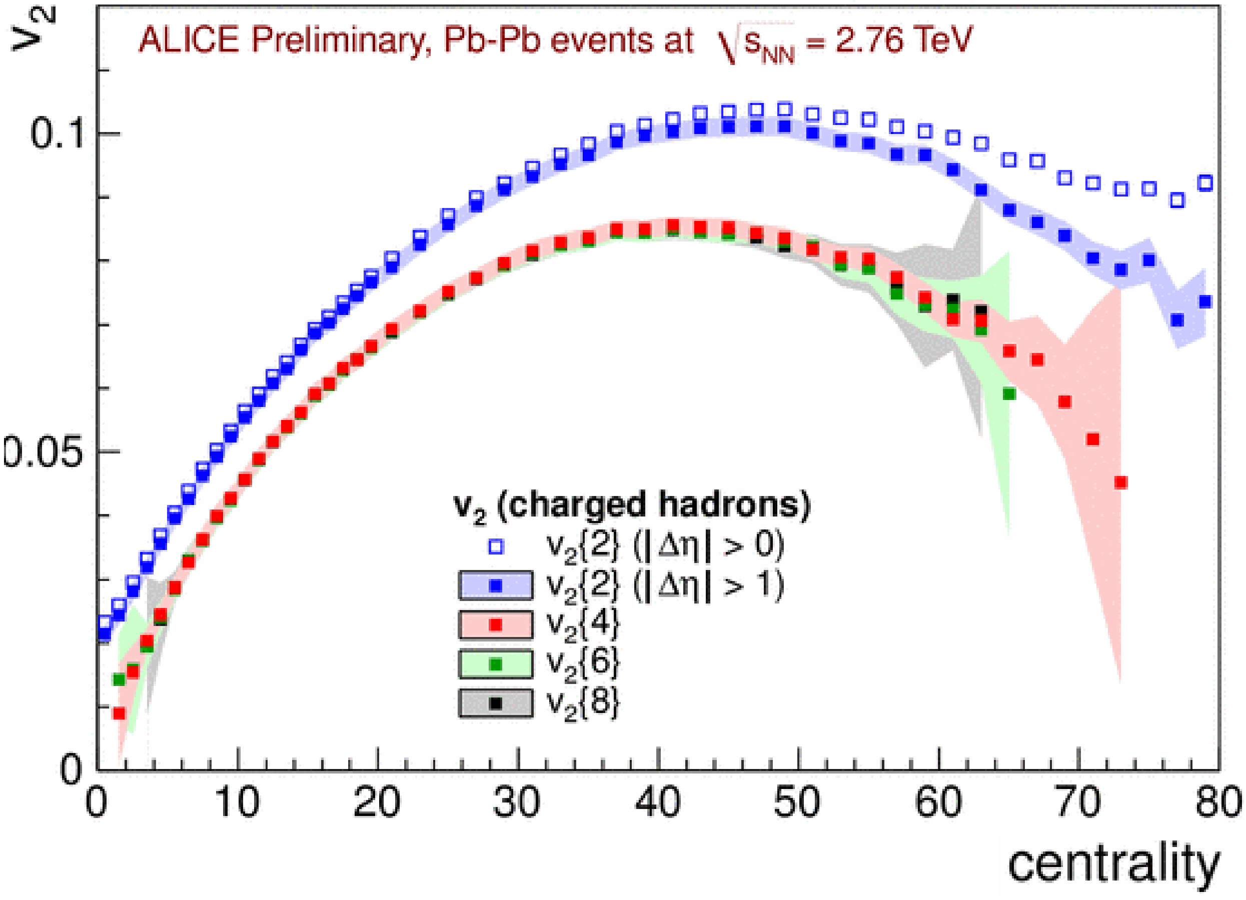
central



peripheral

# 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 (will discuss later)

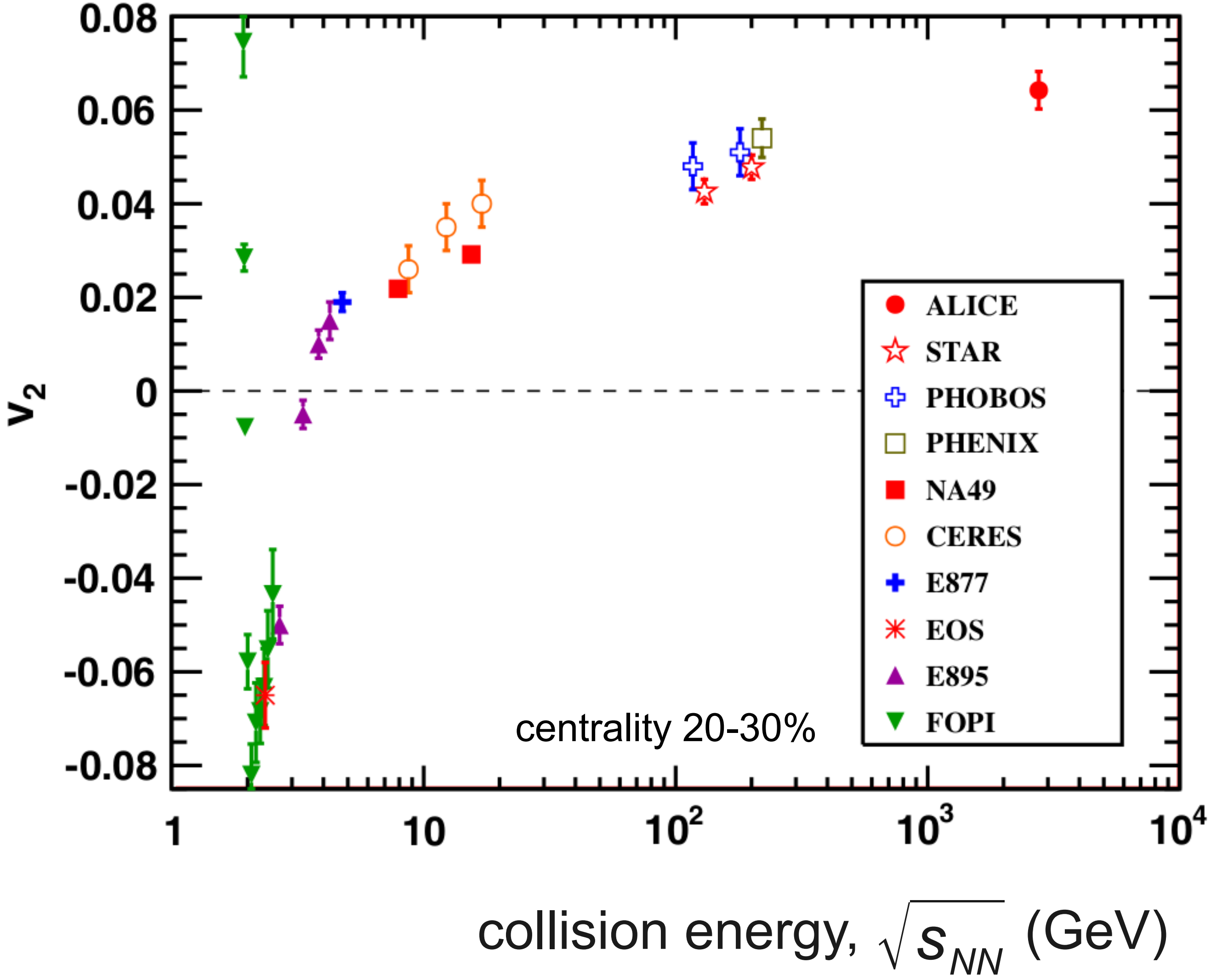
Multi-particle cumulants remove residual non-flow:

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

# Elliptic flow:

# the dominant flow component at the relativistic energies

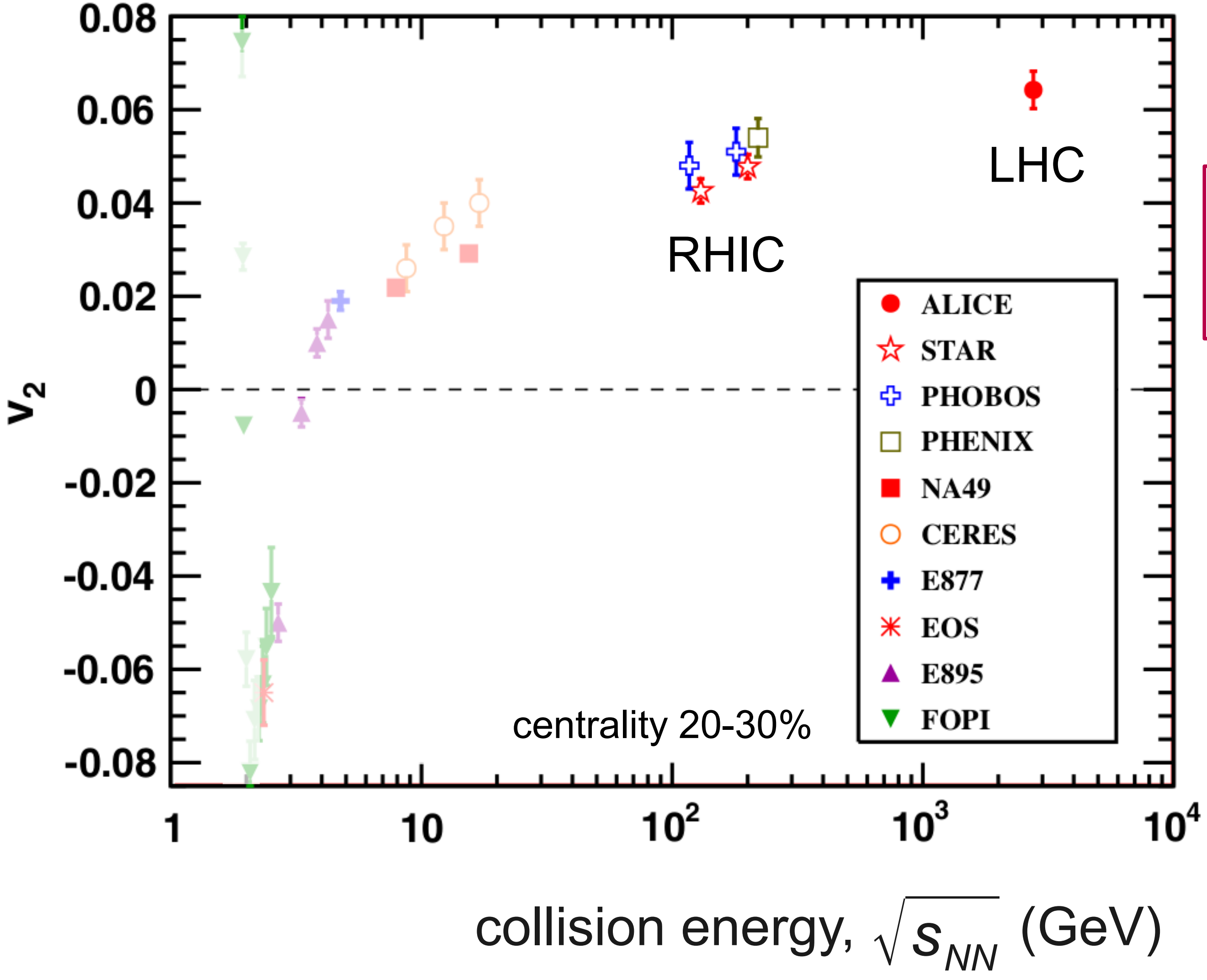
# Elliptic flow vs. collision energy



Experimental results covers about 4 decades of the collision energy

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

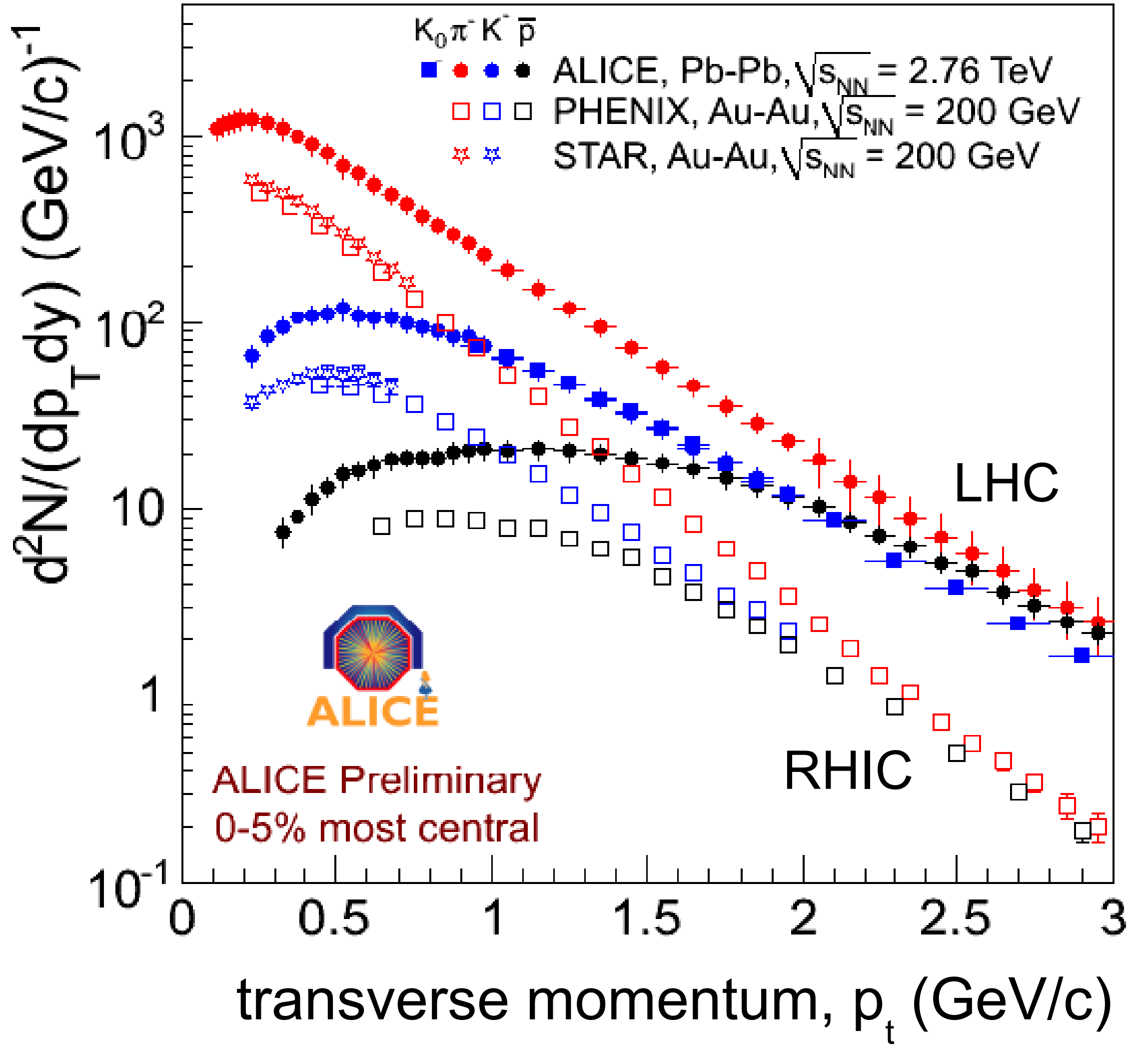
# Elliptic flow: RHIC vs. LHC



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



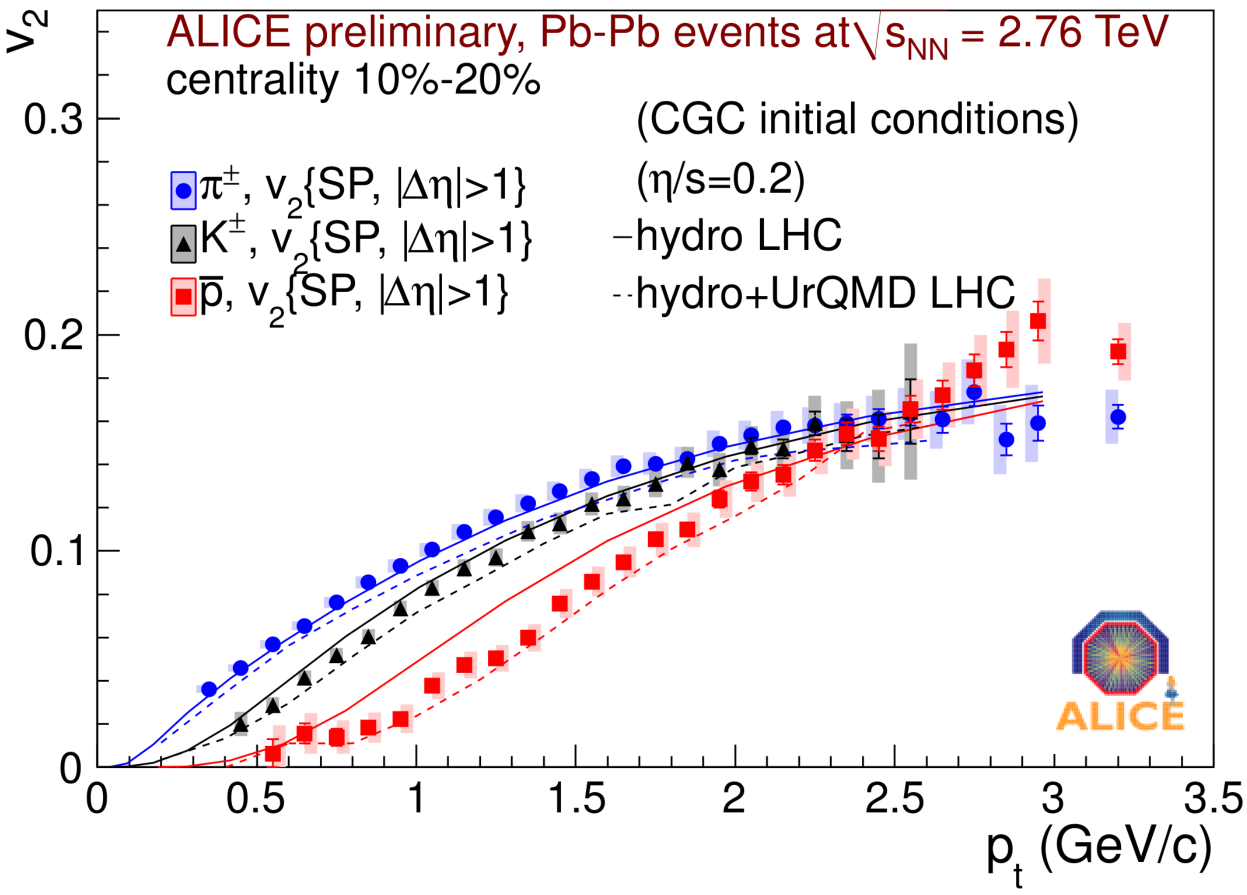
Spectra shapes changed significantly from RHIC to LHC

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 (low $p_t$)



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 $K^{\pm}$:

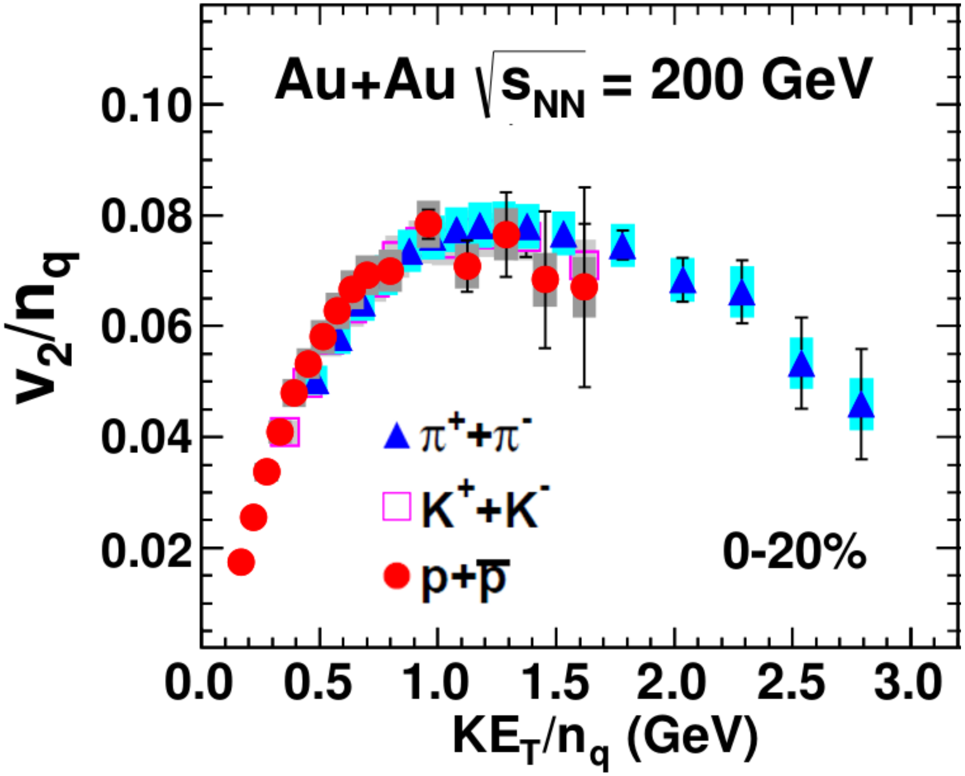
→ sensitivity to QGP viscosity
→ suggest low viscosity

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

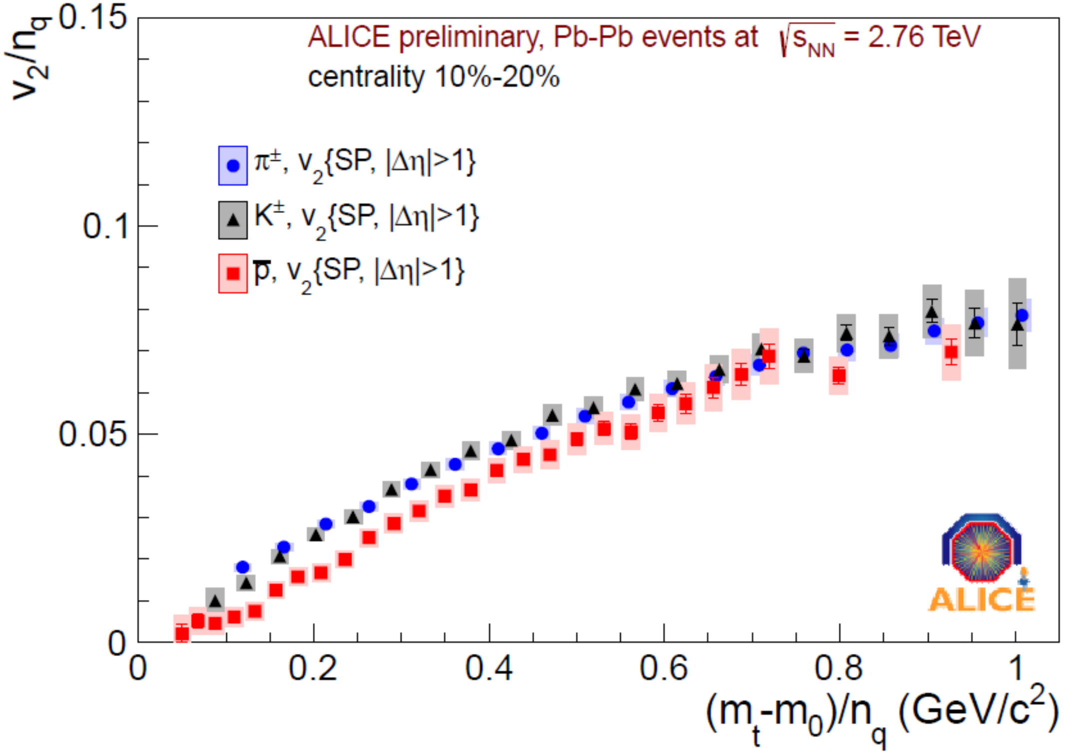
# Constituent number of quarks scaling (mid $p_t$)

PHENIX @ RHIC

arXiv:1203.2644



ALICE @ LHC

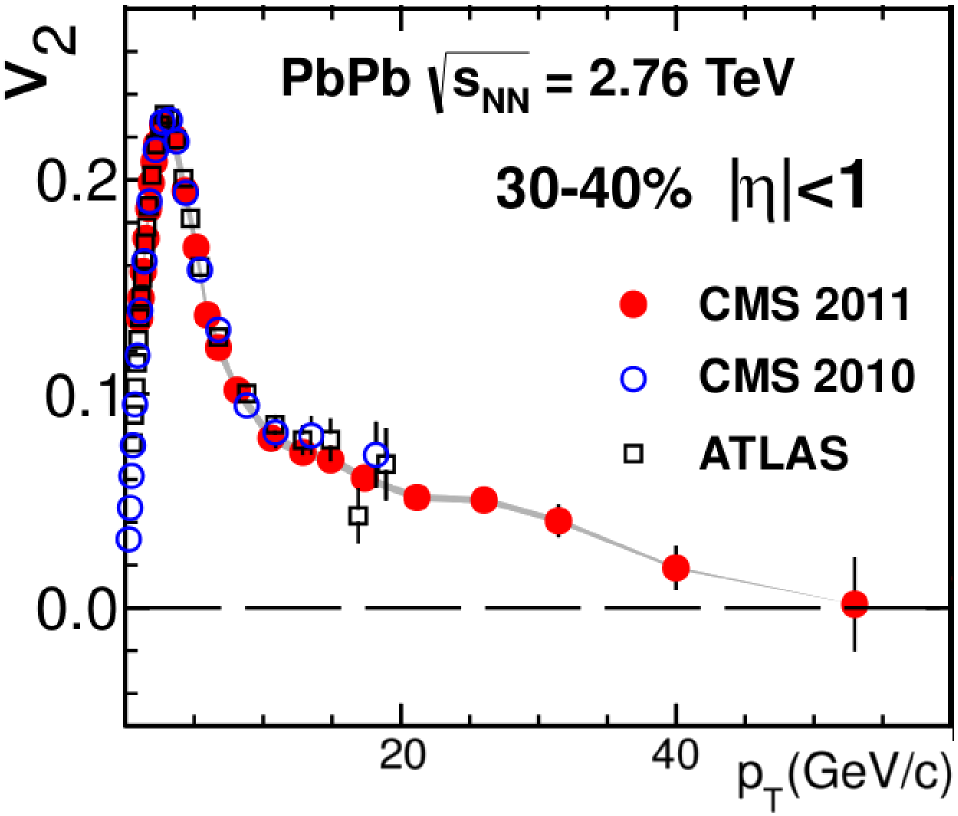


Observe approximate number of quark scaling:

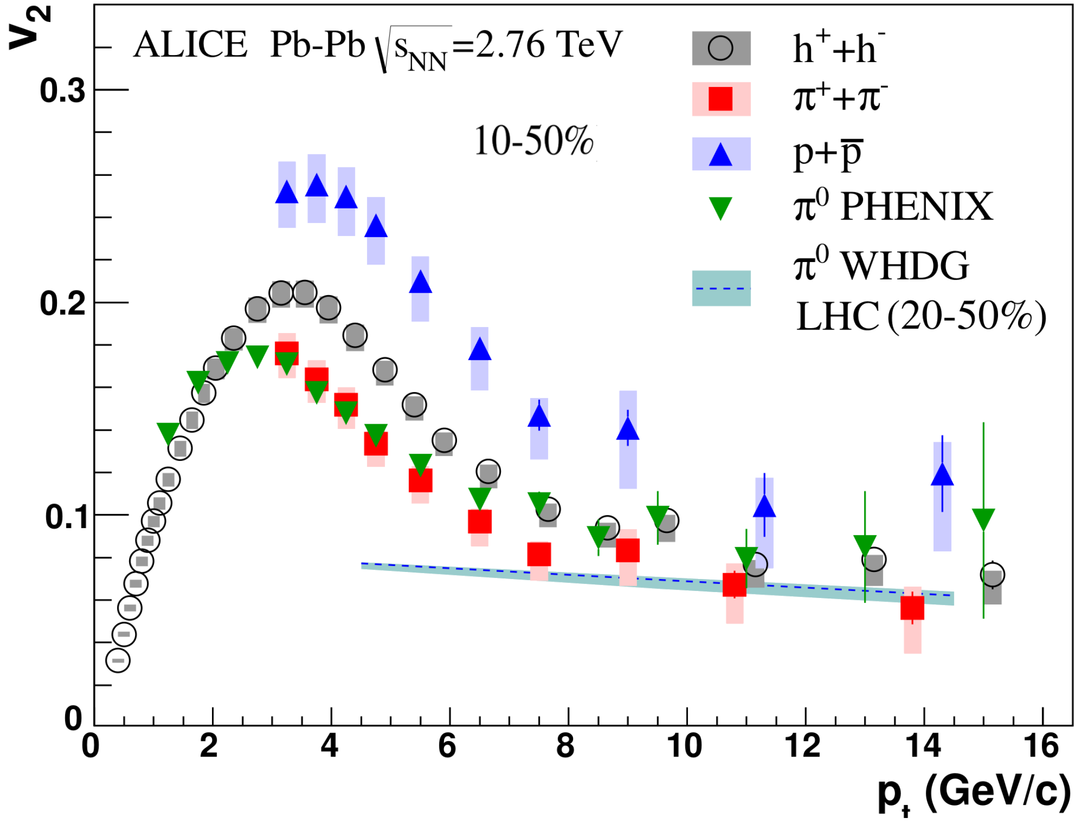
Indication that system evolved through deconfined (QGP) phase

# Azimuthal anisotropy at high transverse momenta, $p_t$

CMS arxiv:1204.1850



ALICE arXiv:1205.5761

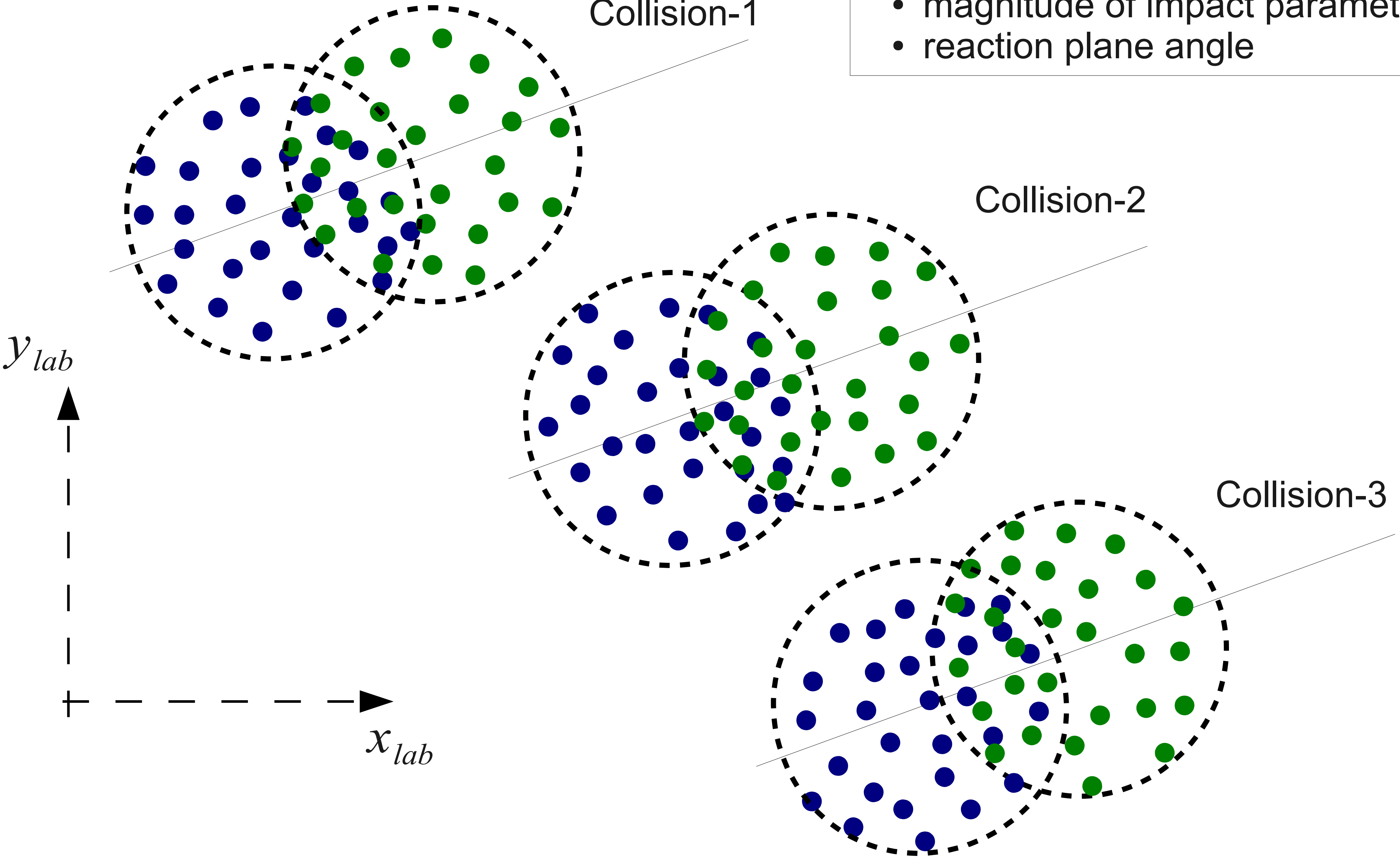


- Non-zero and positive $v_2$ up to $p_t$ ~ 40 GeV/c
  - sensitivity to the jet quenching and parton energy loss
- different $v_{2,3}$ for protons and pions up to $p_t$ ~ 8GeV/c
  - different parton fragmentation in medium

# Flow fluctuations

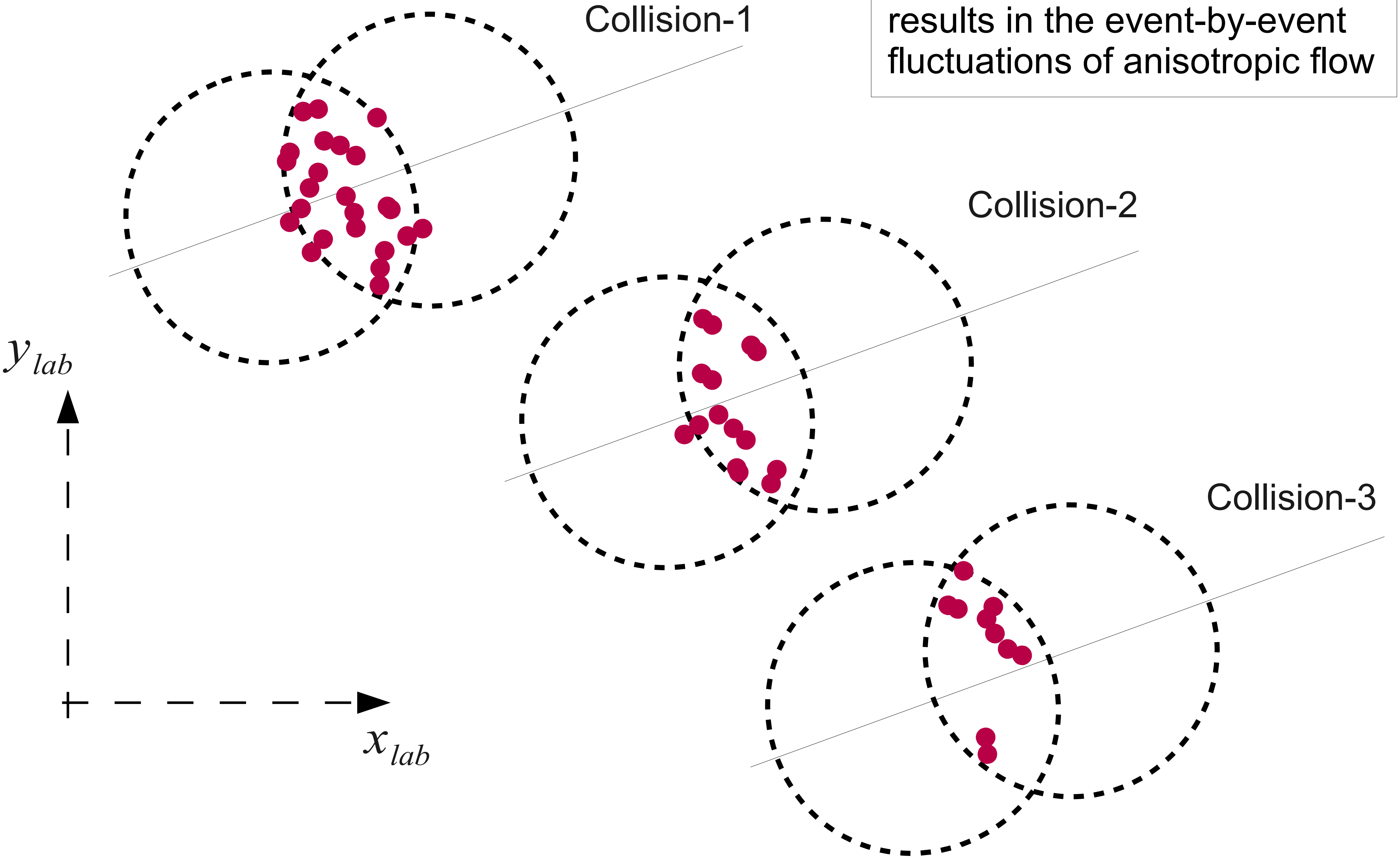
# Experimentally study many collisions

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:

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

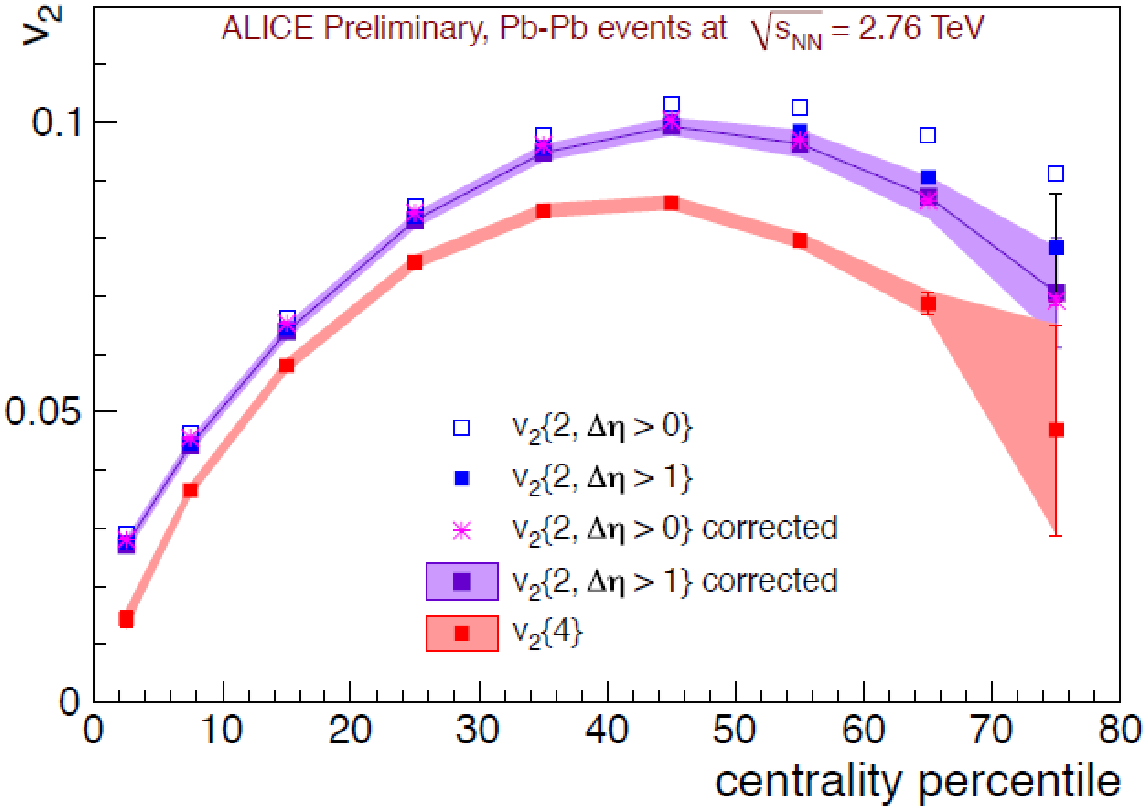
$$\boxed{\langle v_n^2 \rangle \neq \langle v_n \rangle^2}$$

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

$$\boxed{\langle \cos[n(\phi_i - \phi_j)] \rangle = \underbrace{\langle v_n \rangle^2}_{\text{flow}} + \underbrace{\sigma_n^2}_{\text{fluctuations}} + \underbrace{\delta_{n,2}}_{\text{non-flow}}}$$

# 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

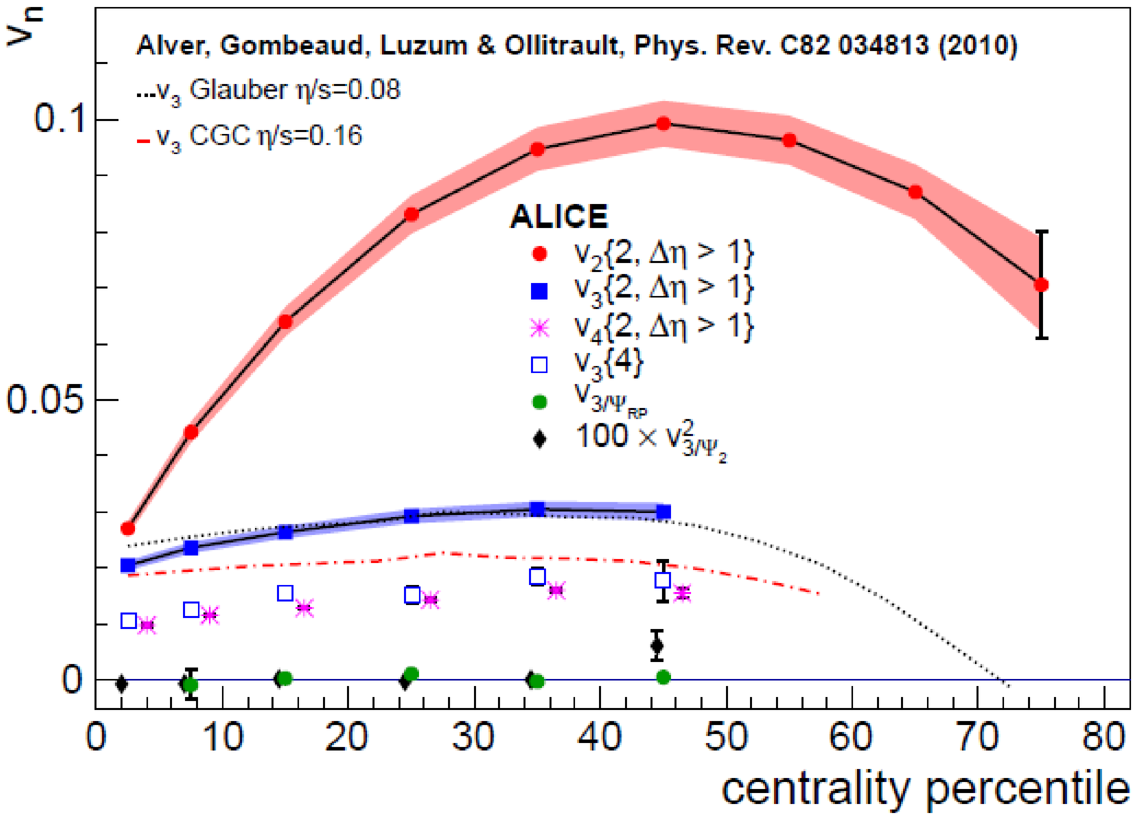
between $v_2^{corr}\{2\}$ and $v_2\{4\}$

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:

$$\langle v_3\rangle = 0$$

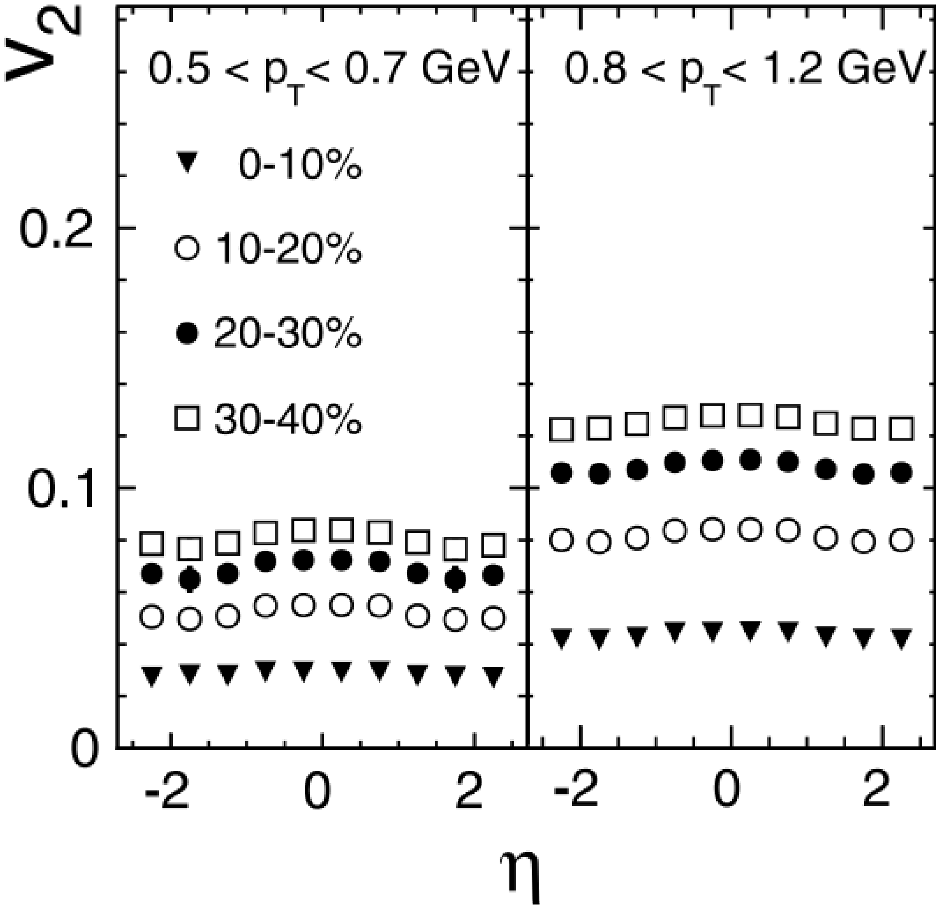
$$v_3^{corr}\{2\} = \sigma_3$$

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

# Many more results from RHIC & LHC: a few examples: $v_1$ and $v_2$ at forward rapidity

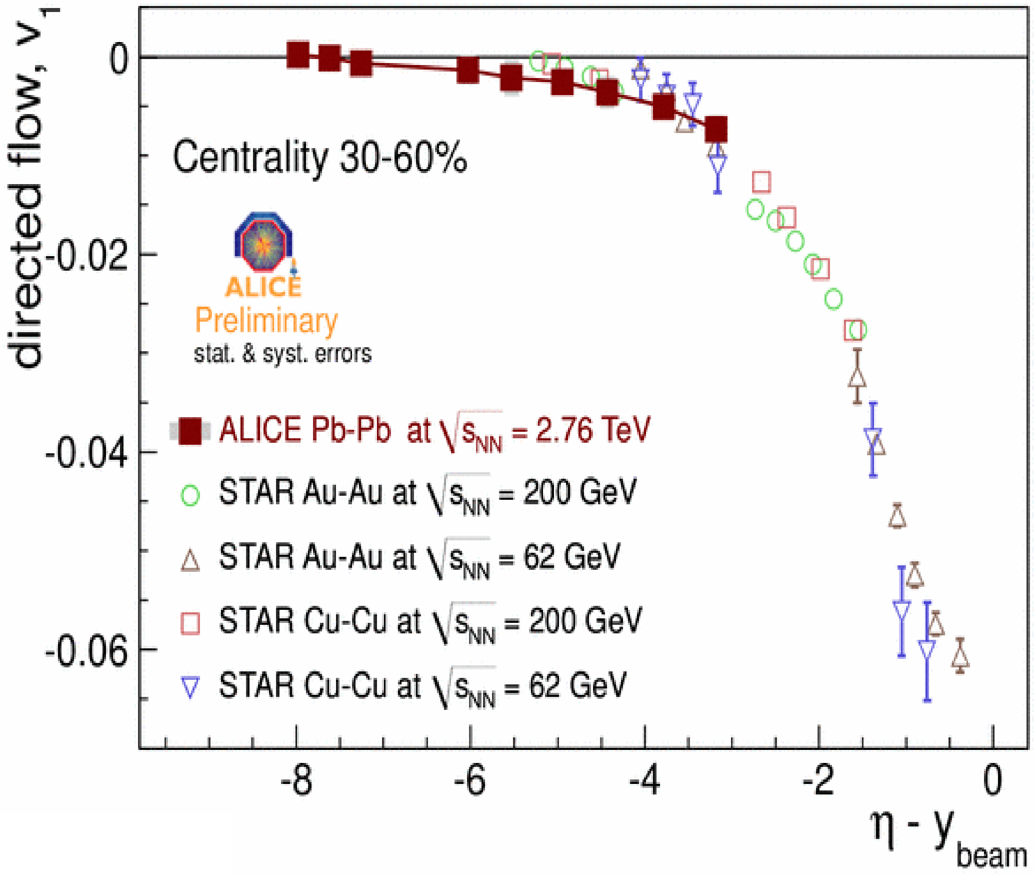
Elliptic flow $v_2$ at forward rapidity

ATLAS PLB 707, 330 (2012)



Directed flow $v_1$ (longitudinal scaling)

ALICE & STAR



Many more interesting results are available from all RHIC and LHC experiments

# Summary

- Anisotropic transverse flow is an important observable to study the evolution of a heavy-ion collision and probe the properties of the created matter (quark-gluon plasma) in a course of a heavy-ion collision

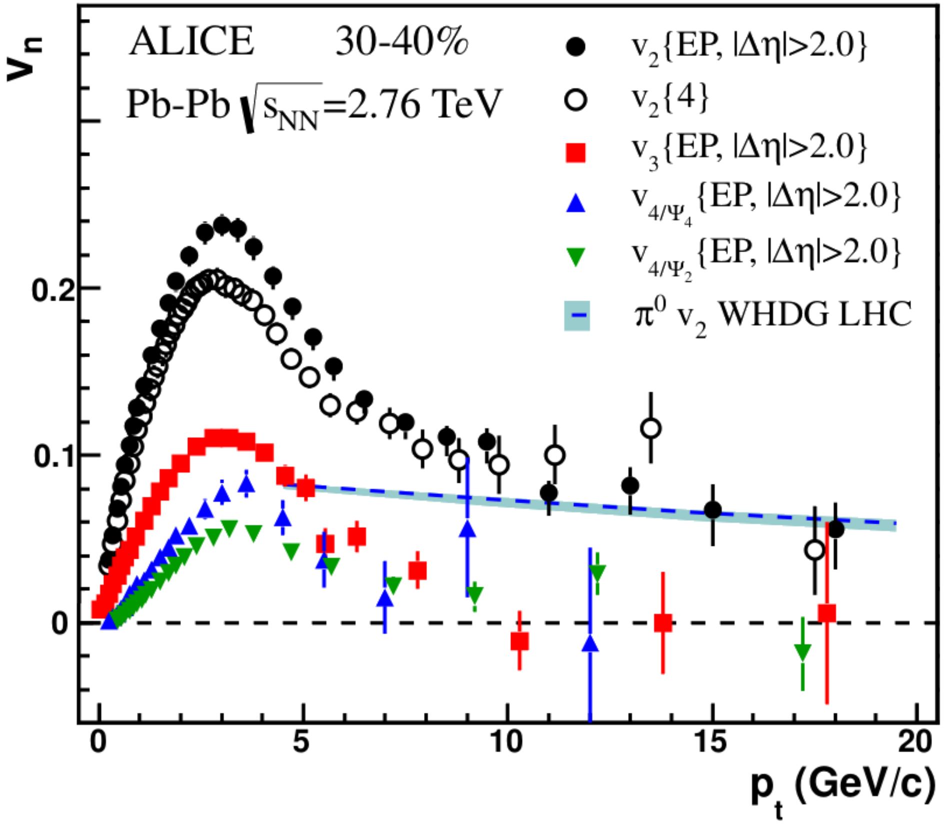
- Anisotropic flow measurements provide experimental constraints on:
  - ✓ Equation of state of the created matter
  - ✓ Transport properties (i.e. viscosity) of the QGP matter
  - ✓ Shape of the initial conditions in a heavy-ion collision
  - ✓ Features of the parton propagation through the dense medium

- In general, helps to understand the origin of the correlations between produced particles in a heavy-ion collision

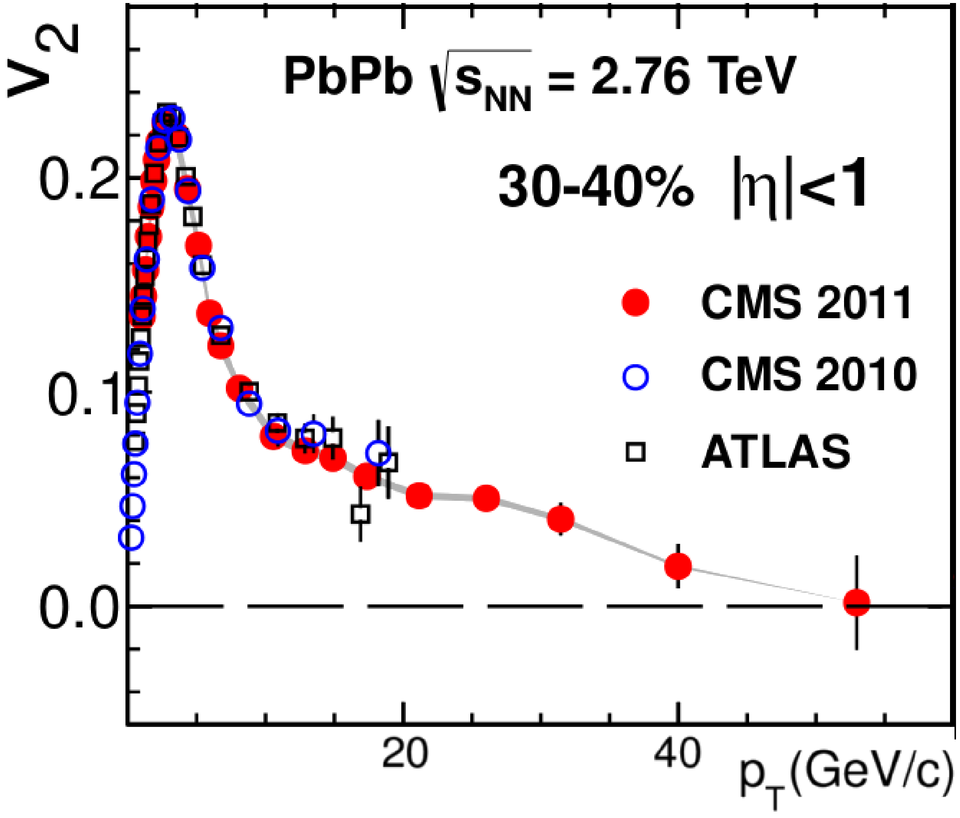
# Backup

# Azimuthal anisotropy at high $p_t$ (higher harmonics)

arXiv:1205.5761



CMS: arxiv:1204.1850



- Non-zero and positive $v_2$ up to $p_t$ ~ 40 GeV/c
  - sensitivity to the parton energy loss mechanism
- $v_{3,4}$ consistent with zero at high $p_t$