
# Pomiary azymutalnej anizotropii w zderzeniach ciężkich jonów w eksperymencie ATLAS

Seminarium WFiIS, 06 marca 2020

Klaudia Maj

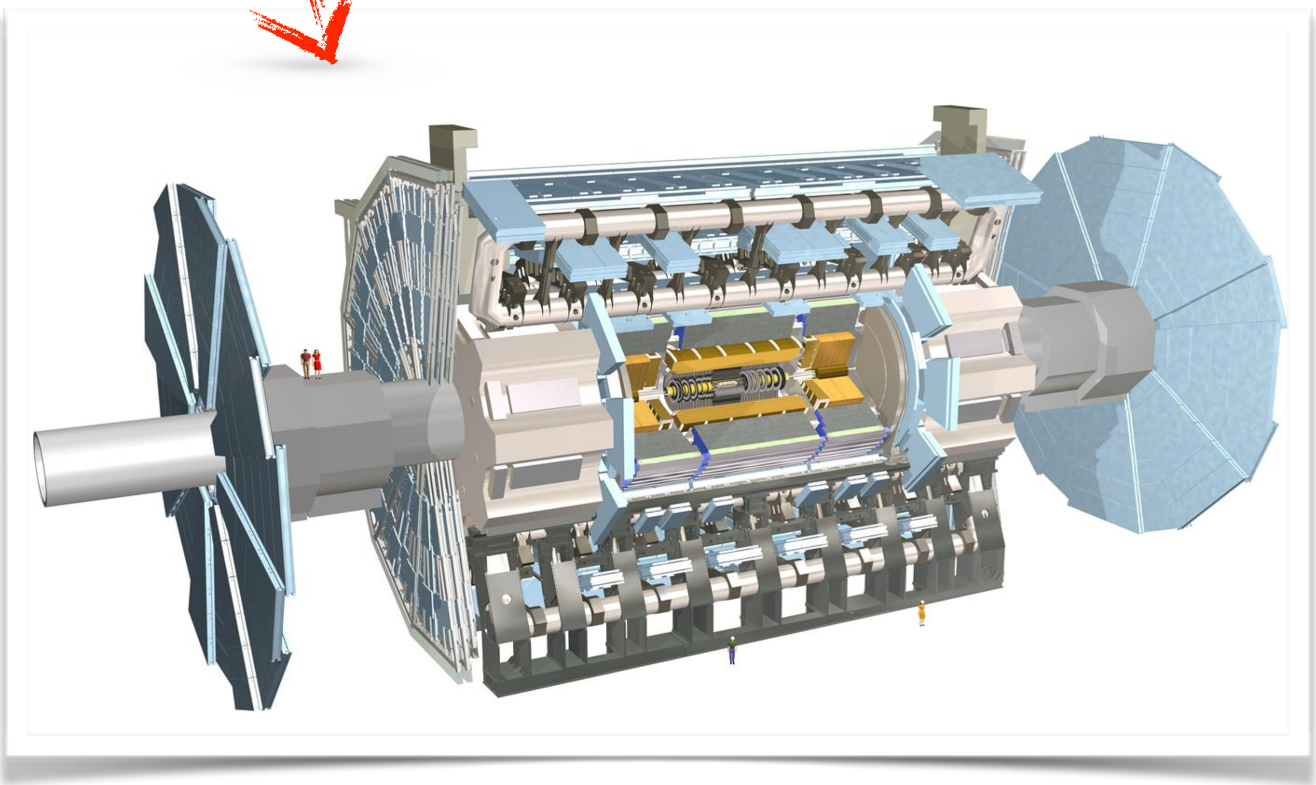
# The Large Hadron Collider (LHC)




- The largest particle accelerator located at CERN in Switzerland
- 4 main experiments at LHC: ATLAS, ALICE, CMS and LHCb
- Goal: searching for new physics in pp and Pb+Pb collisions – insight into the initial state of the Universe

# The Large Hadron Collider (LHC)

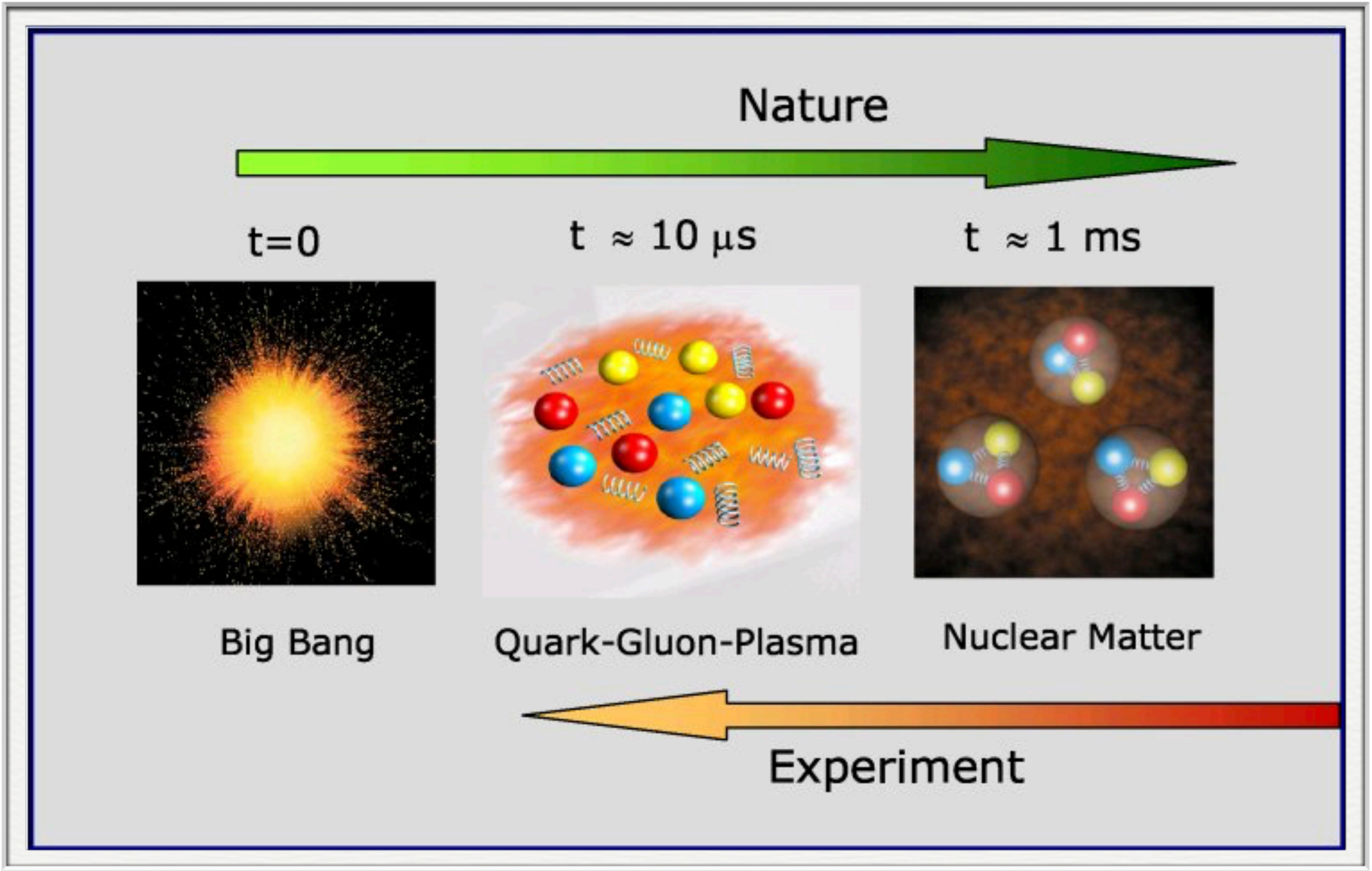


- The largest particle accelerator located at CERN in Switzerland
- 4 main experiments at LHC: ATLAS, ALICE, CMS and LHCb
- Goal: searching for new physics in pp and Pb+Pb collisions – insight into the initial state of the Universe

# Quark-gluon plasma (QGP)

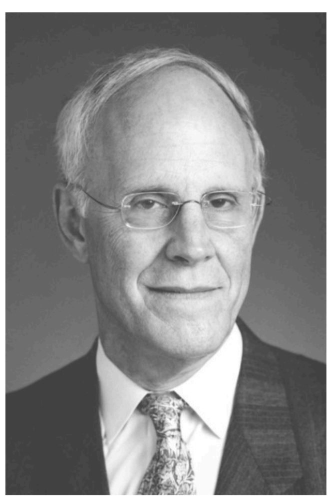




# Asymptotic freedom

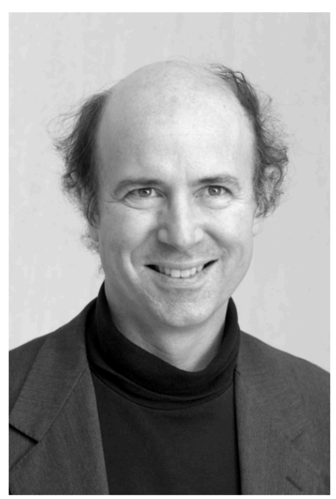

**The Nobel Prize in Physics 2004**

„for the discovery of asymptotic freedom in the theory of the strong interaction"

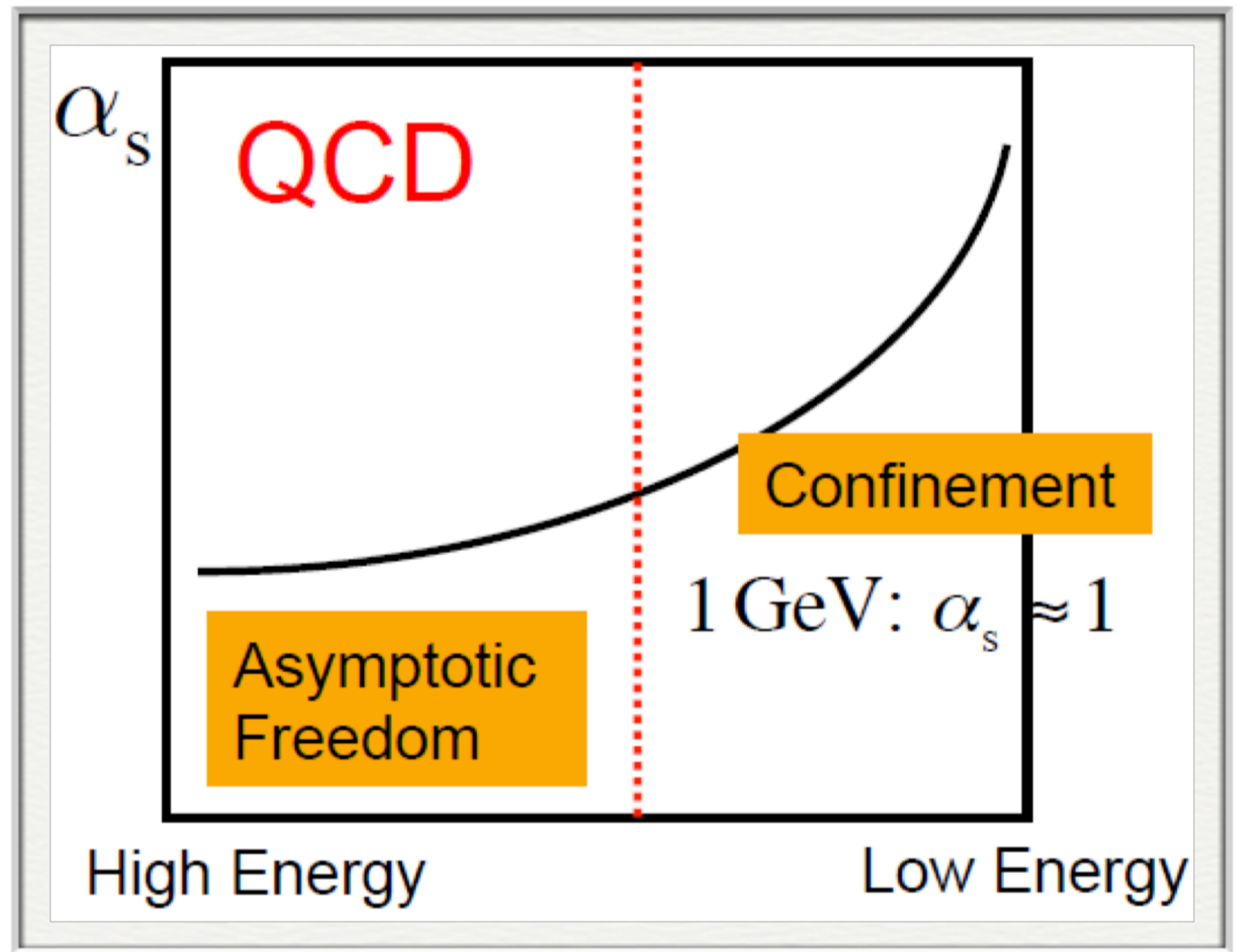


**Gross**

**Politzer**



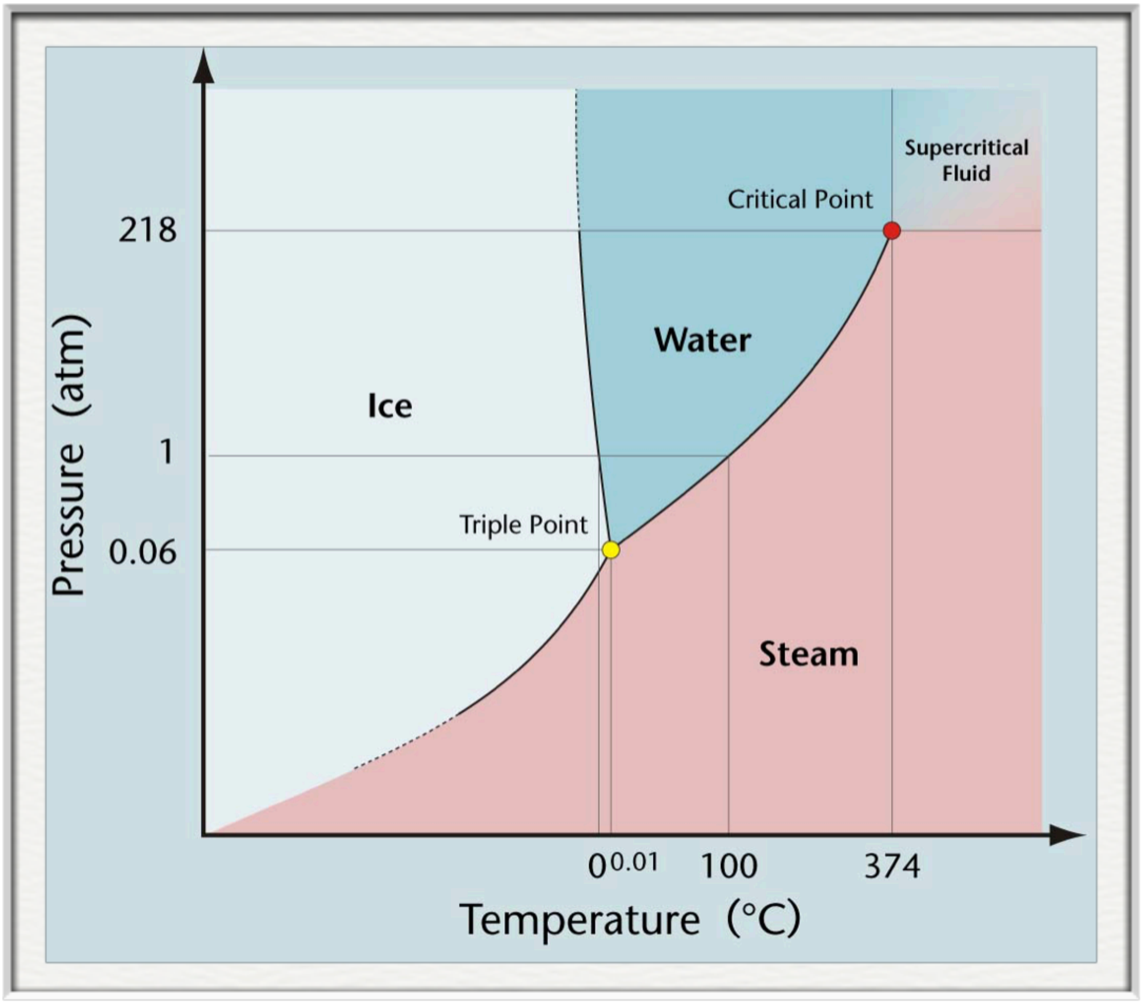
**Wilczek**



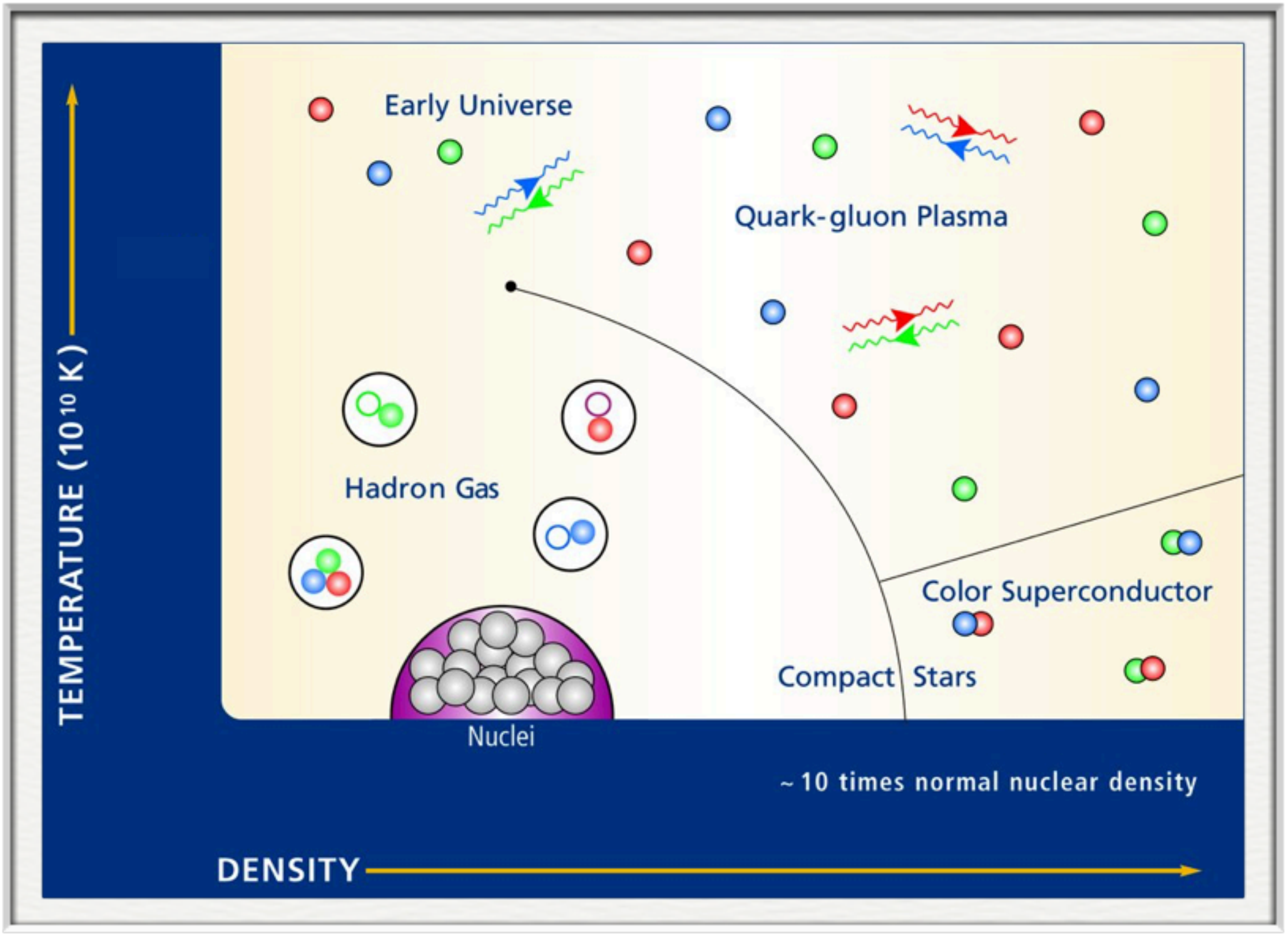
# Phase diagram of nuclear matter



## Phase diagram of water



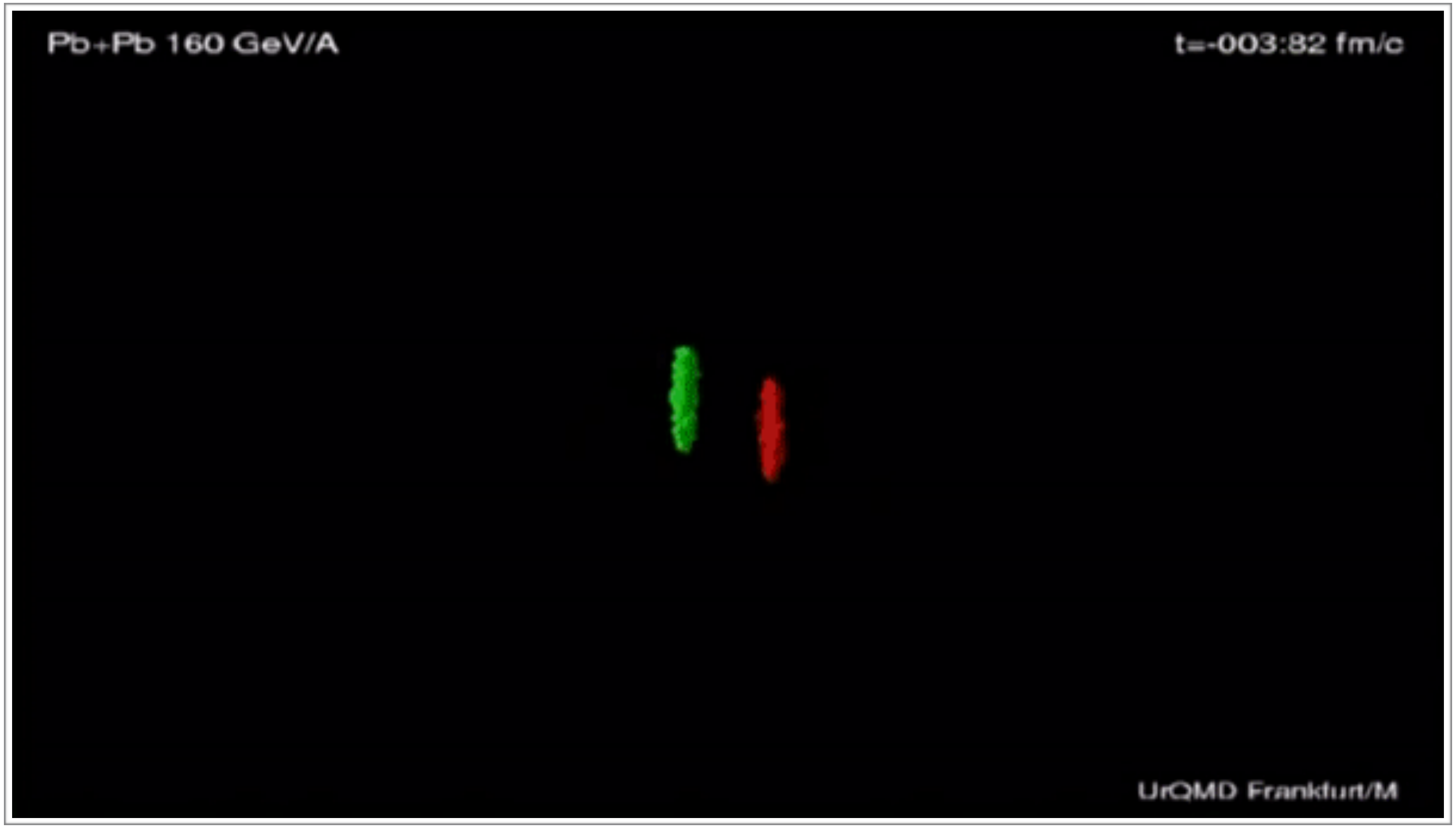

## Phase diagram of nuclear matter



# Heavy-ion collision



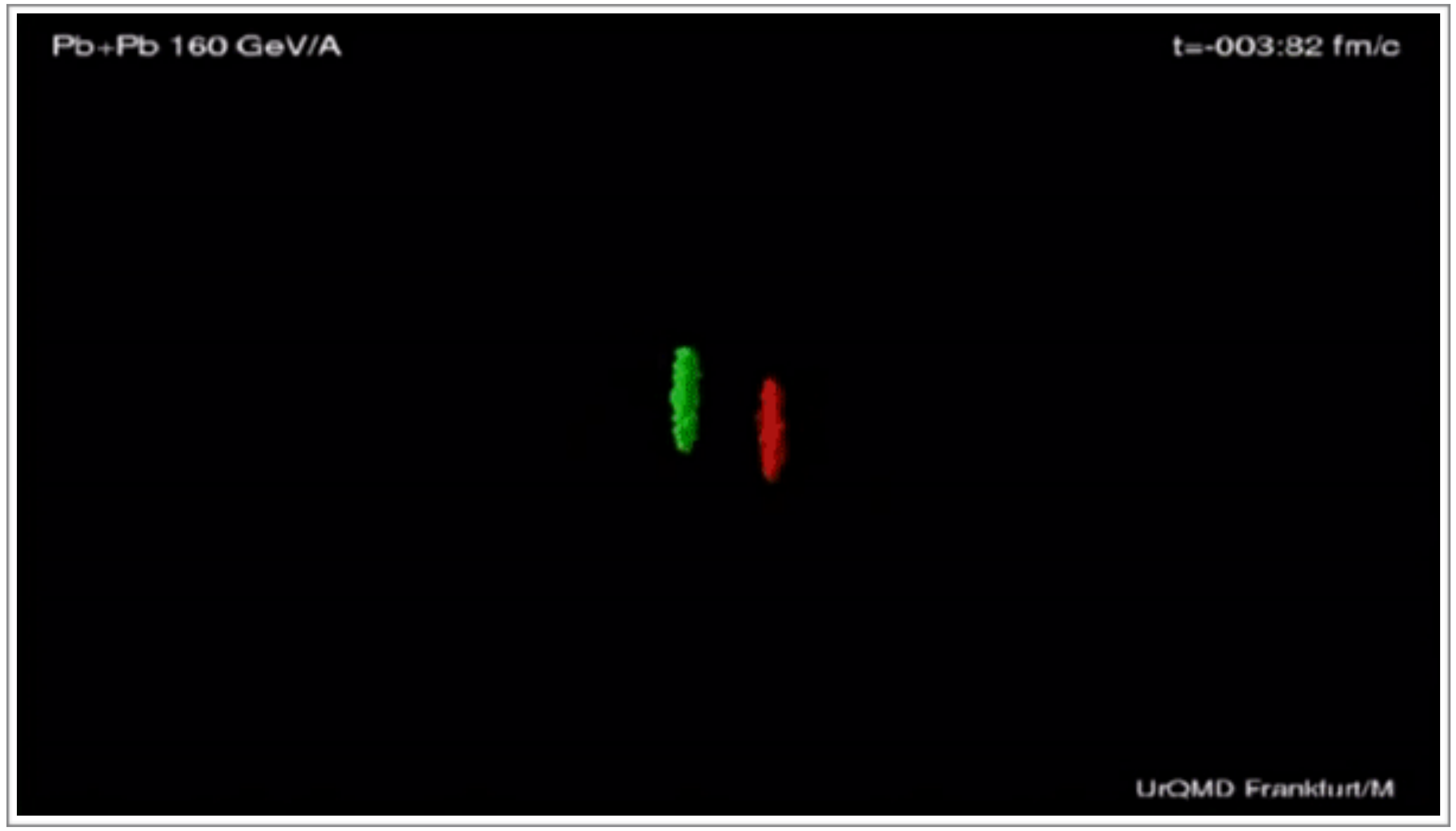
**Quark-Gluon Plasma** is produced and probed in relativistic heavy-ion collisions

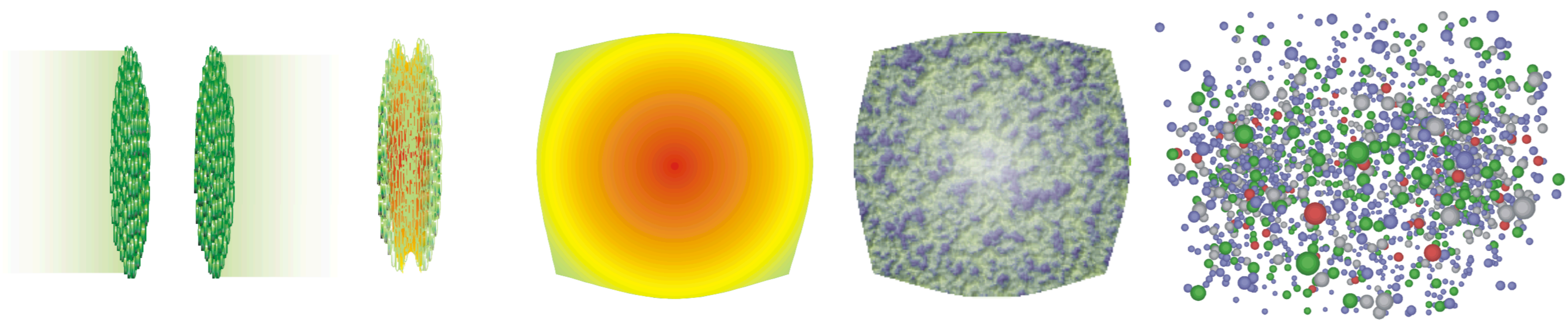



z (beam direction)

# Heavy-ion collision





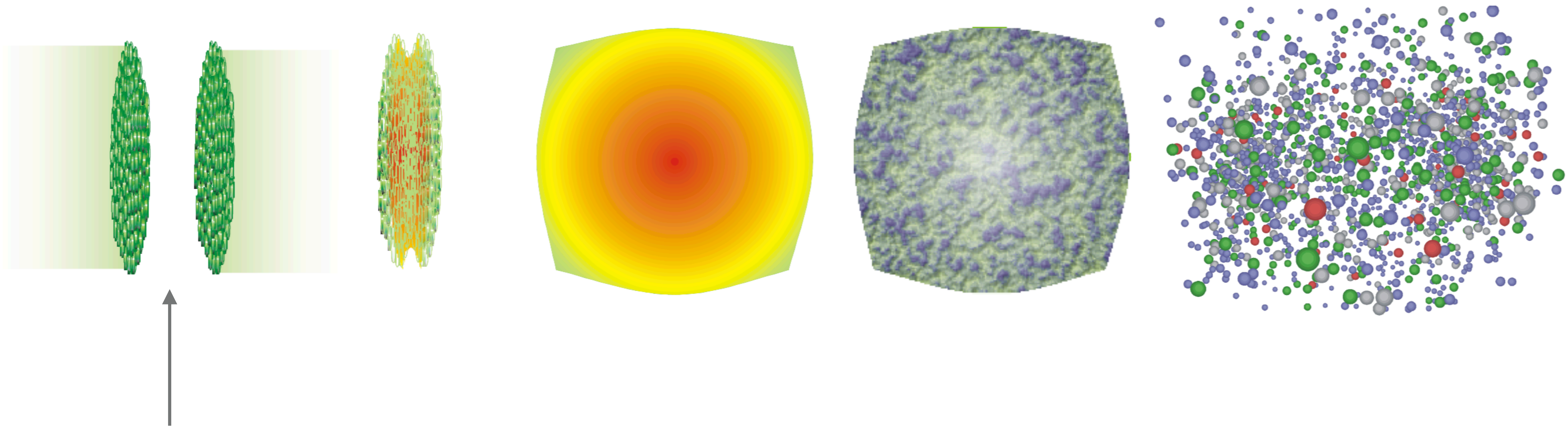



Quark-gluon plasma lifetime: ~10-15 fm/c (~$10^{-23}$s)

→ long enough to have a time evolution and bulk properties

# Heavy-ion collision



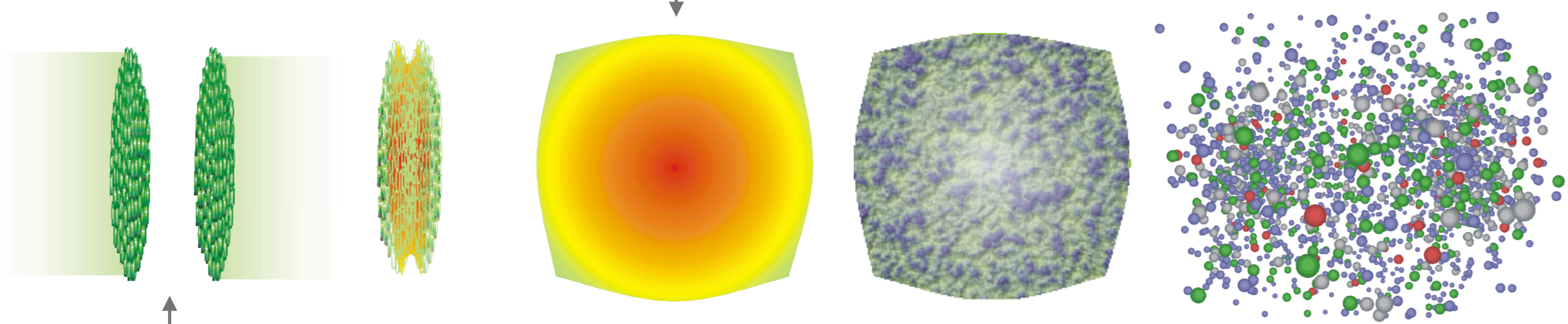


incoming Lorentz
contracted nuclei

# Heavy-ion collision



quark-gluon plasma

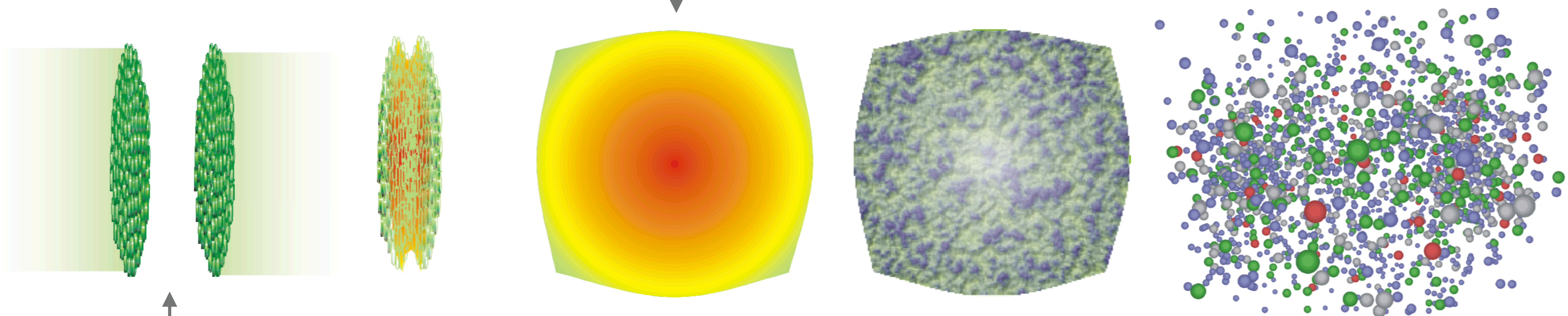


incoming Lorentz
contracted nuclei

# Heavy-ion collision



quark-gluon plasma

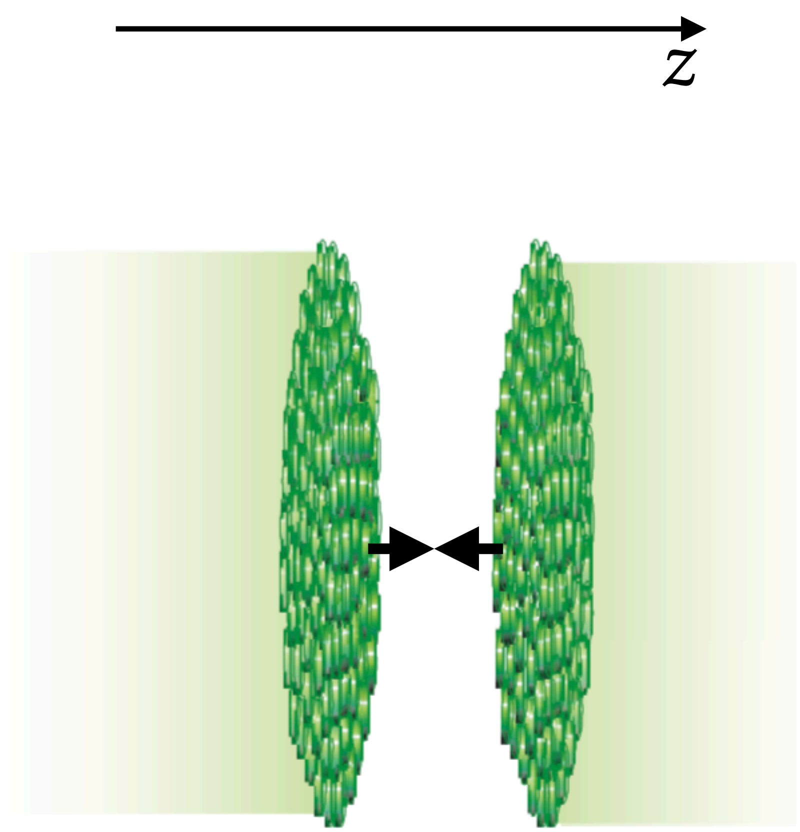


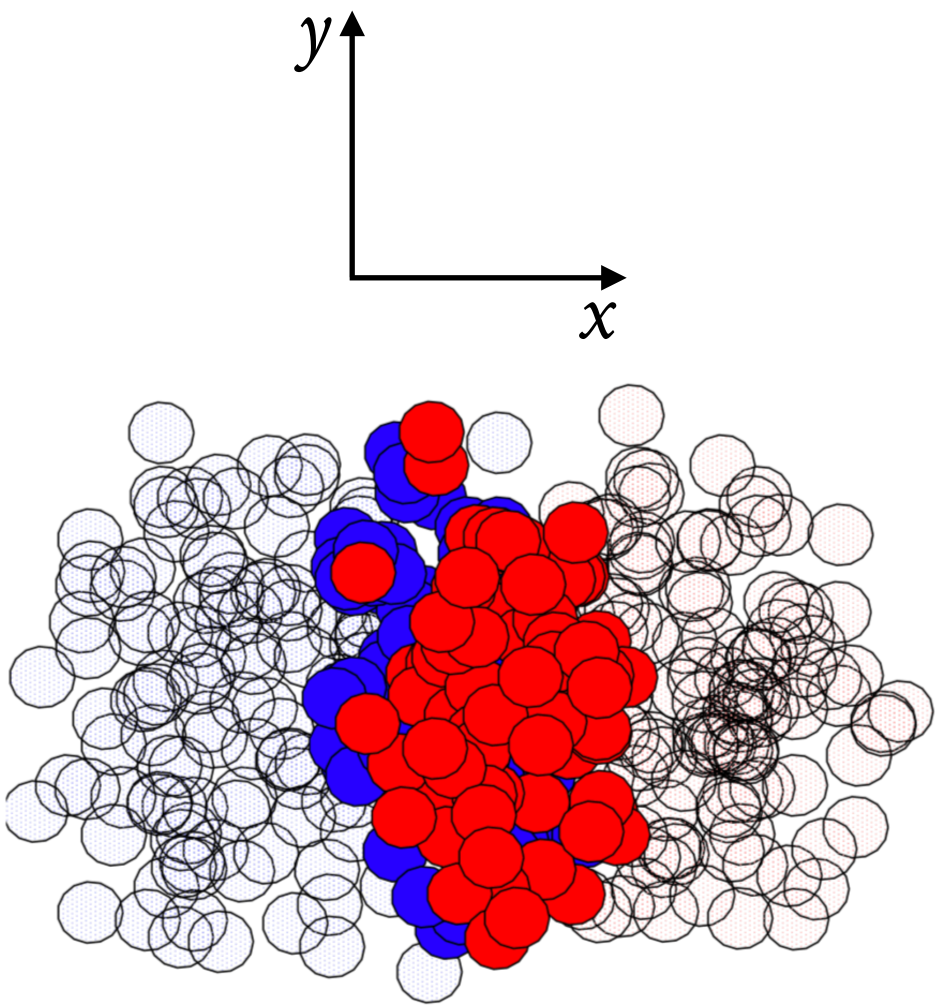
incoming Lorentz contracted nuclei

hadrons headed to the detector

# Collision geometry

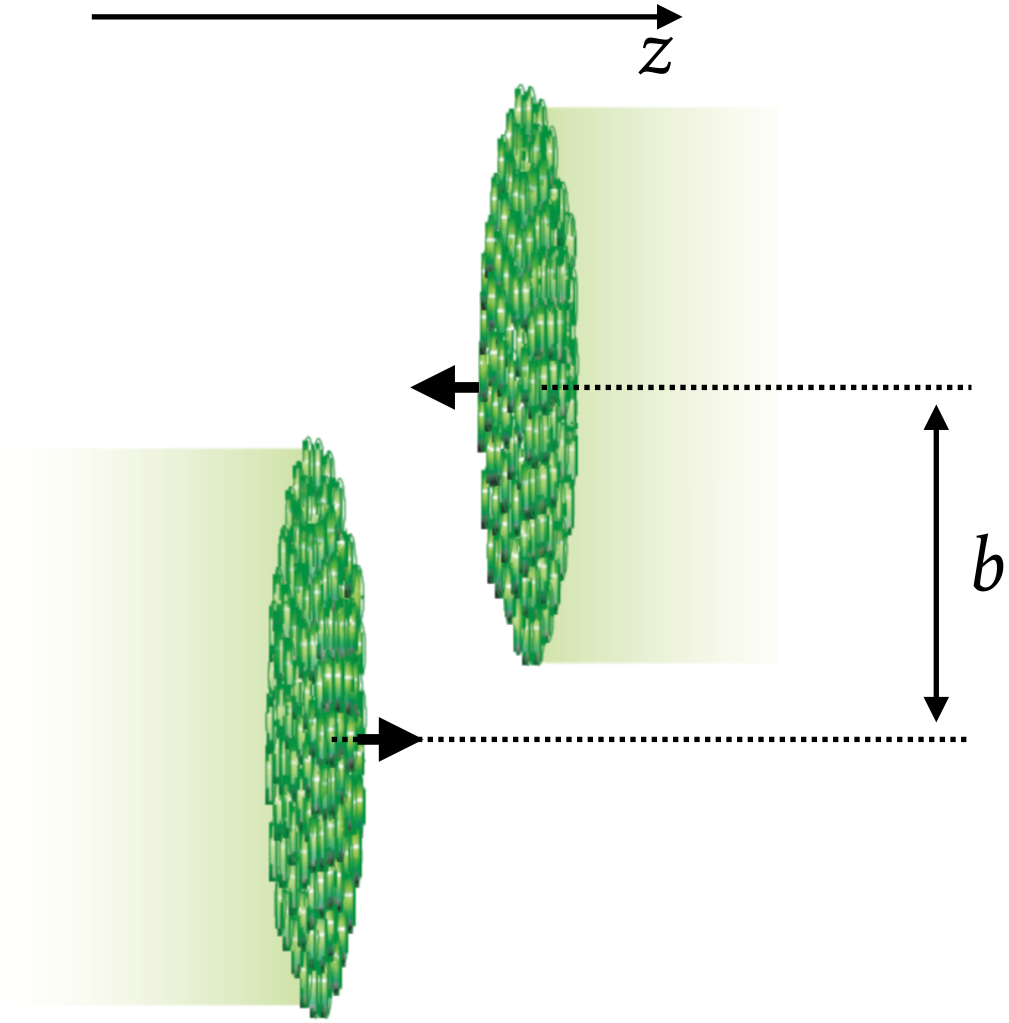


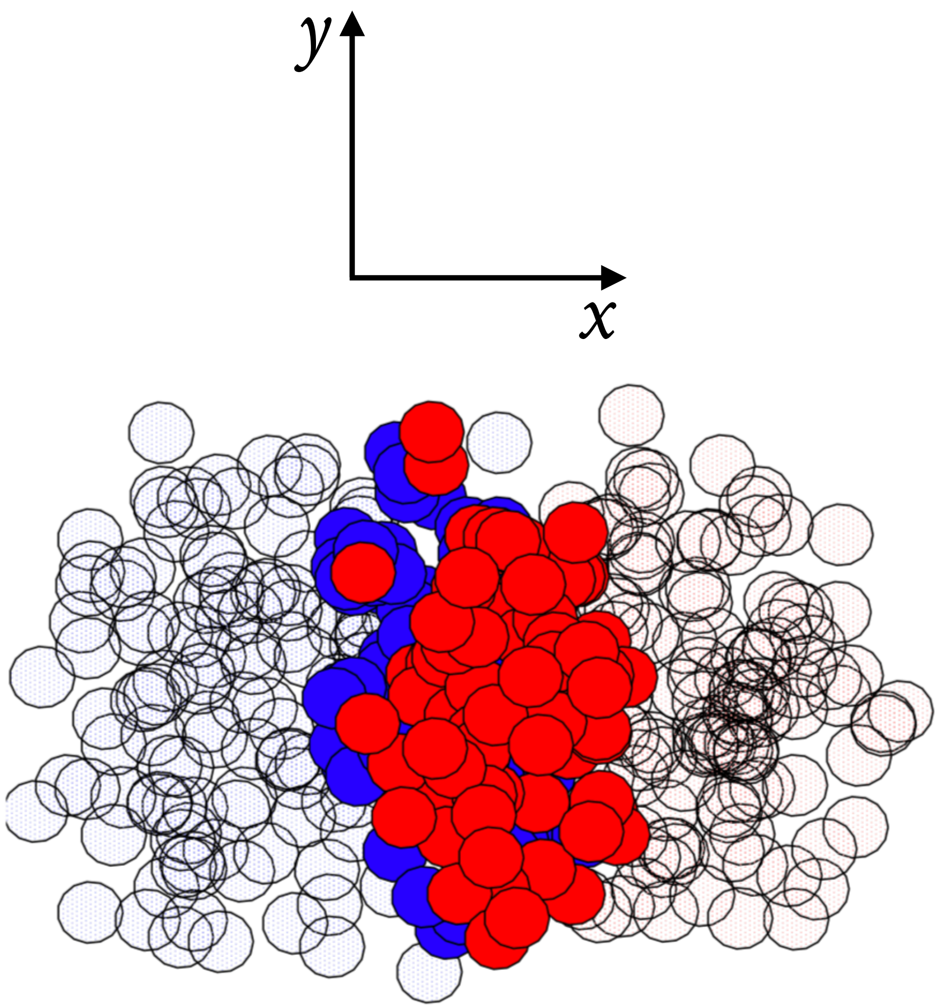


# Collision geometry





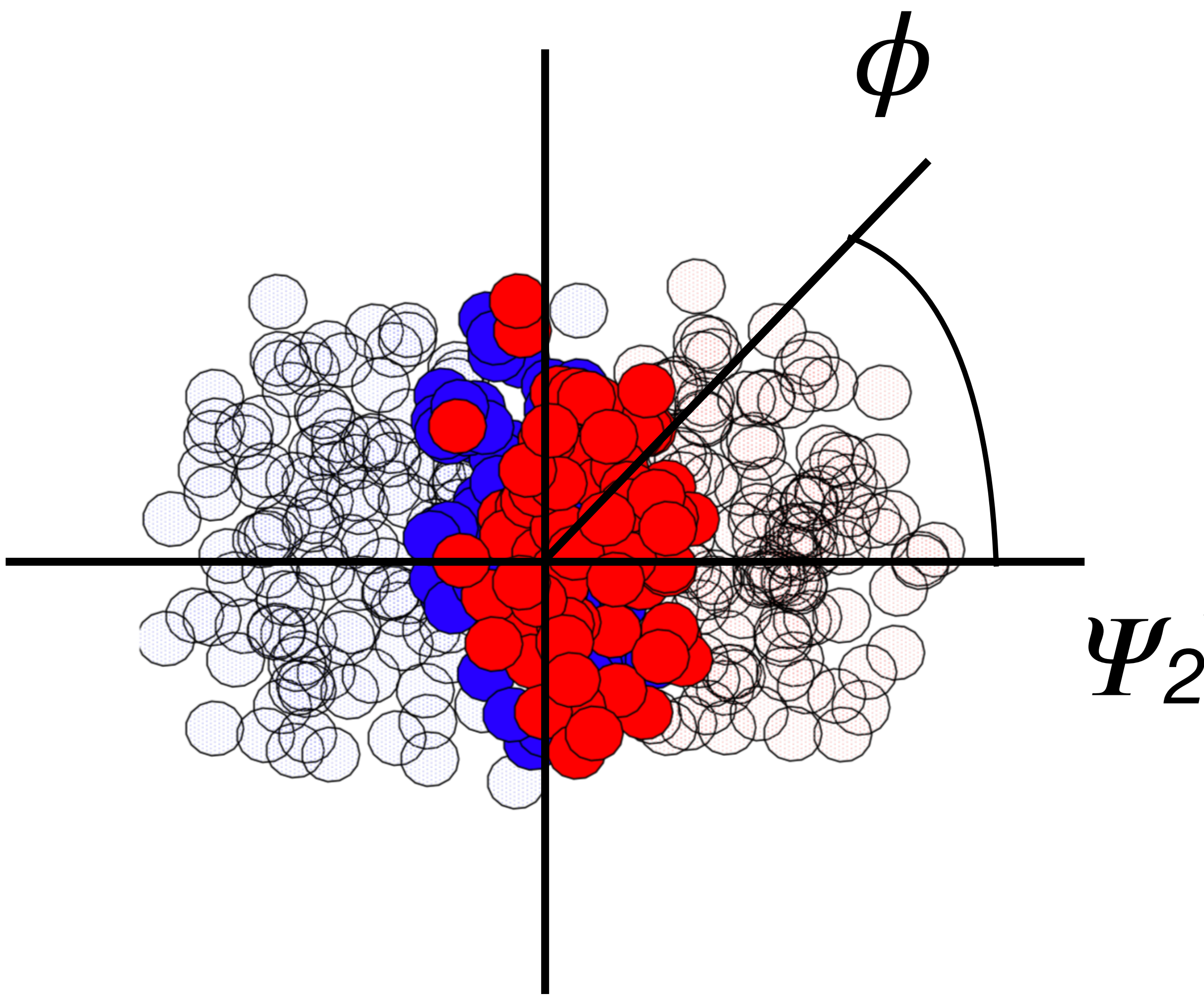



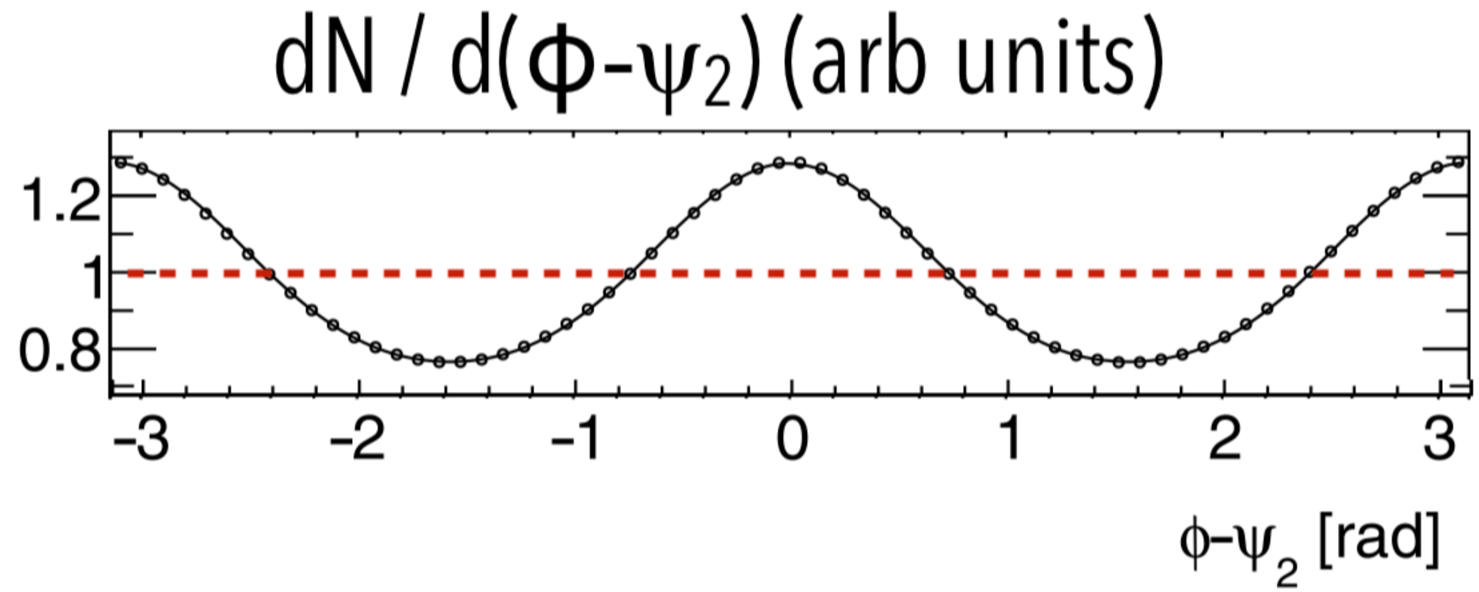

- Geometry of a collision depends on the **impact parameter** and **event-by-event** fluctuations
- Observables sensitive to geometry provide a powerful tool to study the quark-gluon plasma

# Collision geometry

**before the collision:** orientation of the nuclei

**after the collision:** angular particles distributions

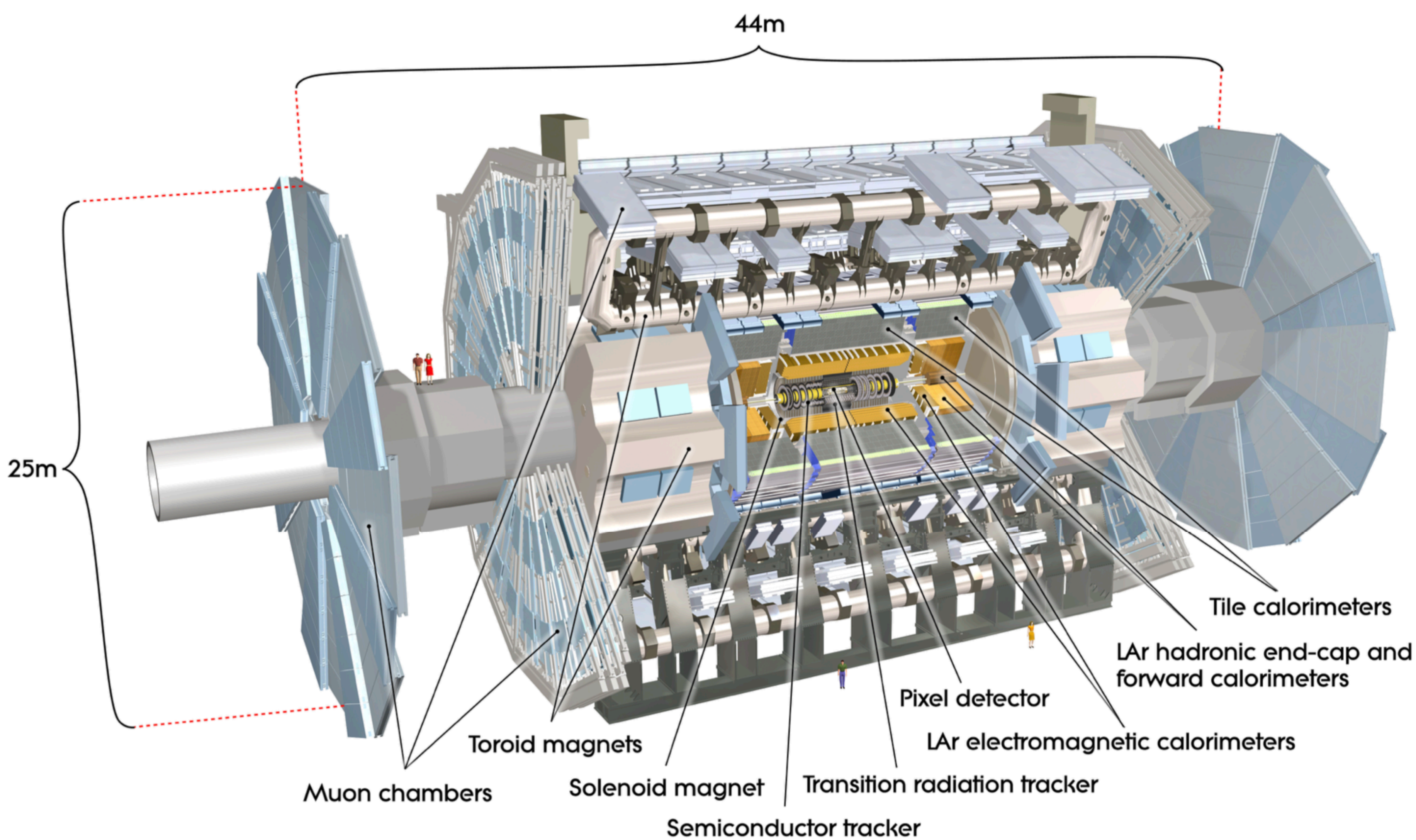



**Reaction plane**
plane defined by beam direction and impact parameter

# ATLAS detector






ATLAS detector is excellent tool for study the azimuthal anisotropy:

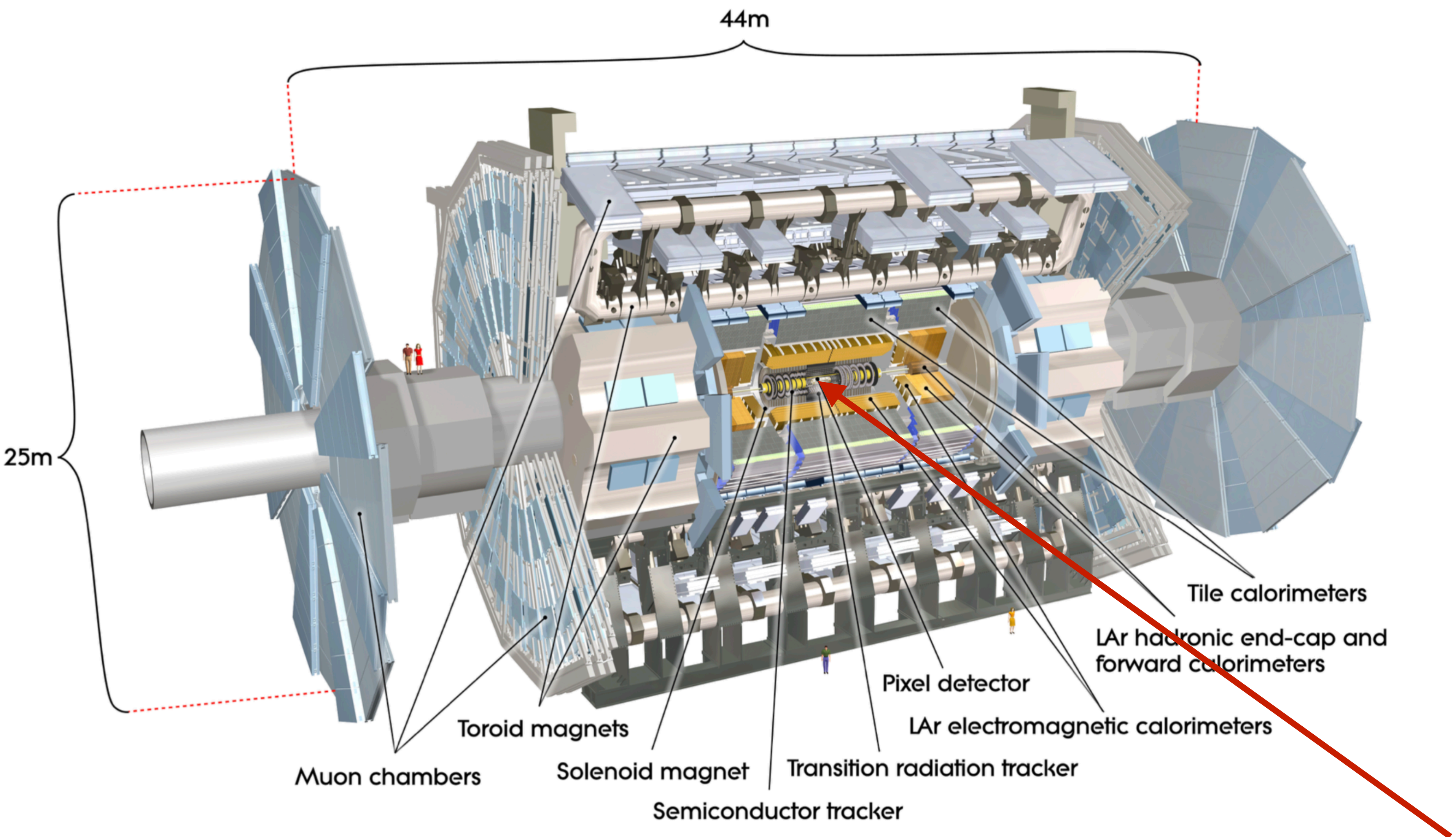
$\phi$ - full azimuthal acceptance

$\eta$ - broad pseudo rapidity coverage $$\eta = -\ln\left[\tan(\frac{\theta}{2})\right]$$

$p_T$ - transverse momentum $$p_T = \sqrt{p_x^2 + p_y^2}$$

# Measuring anisotropy






**Inner Detector**
charged particles with $|\eta| < 2.5$

ATLAS detector is excellent tool for study the azimuthal anisotropy:

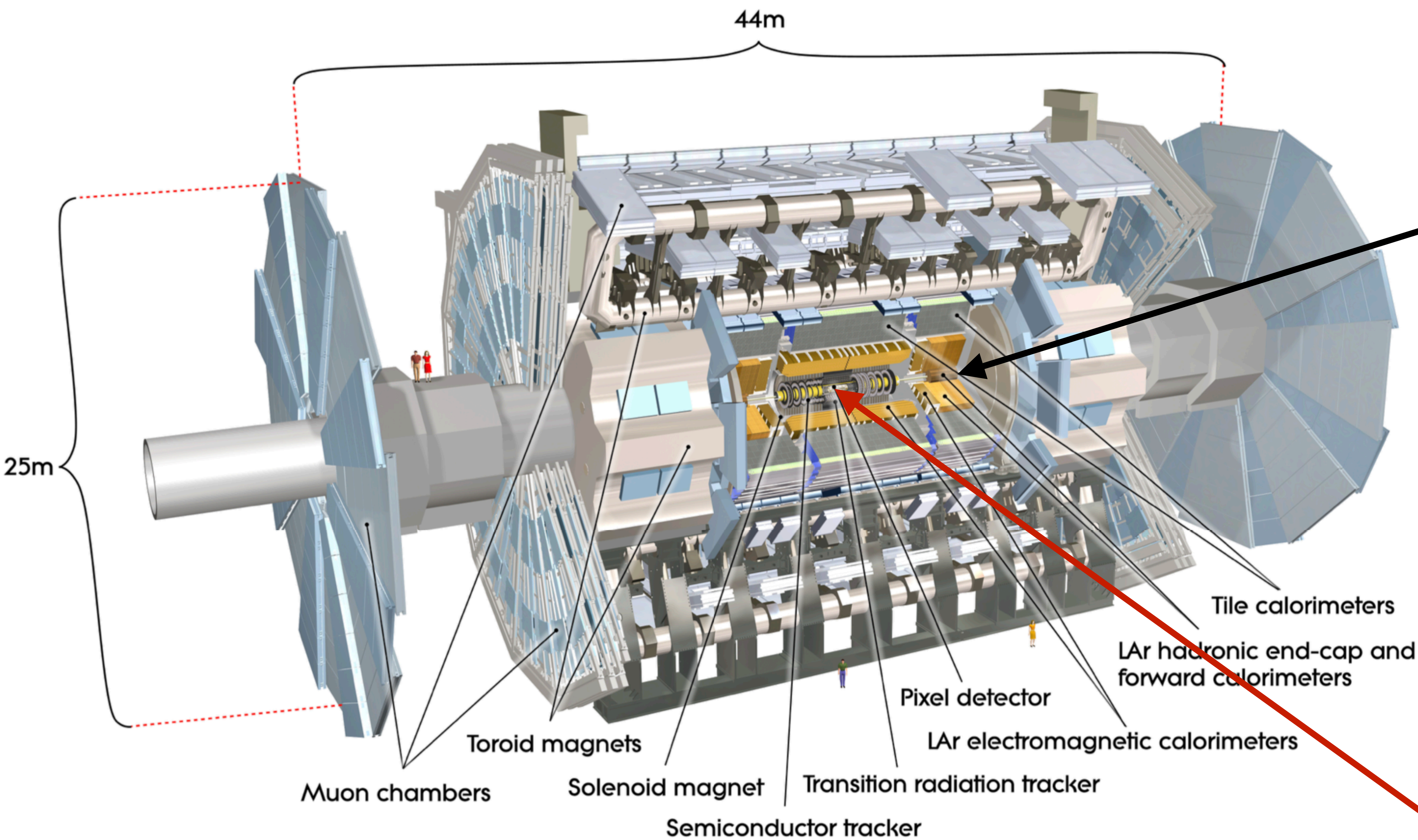
$\phi$ - full azimuthal acceptance

$\eta$ - broad pseudo rapidity coverage $$\eta = -\ln\left[\tan(\frac{\theta}{2})\right]$$

$p_T$ - transverse momentum $$p_T = \sqrt{p_x^2 + p_y^2}$$

# Measuring anisotropy






**Forward Calorimeter**
$3.2 < |\eta| < 4.8$

Particle energy measurement → $\Psi_2$ & event centrality

$$\Psi_2 = \frac{1}{2}\tan^{-1}\left(\frac{\sum E_{\mathrm{T},i}^{\mathrm{tower}} w_i \sin(2\phi_i)}{\sum E_{\mathrm{T},i}^{\mathrm{tower}} w_i \cos(2\phi_i)}\right)$$

**Inner Detector**
charged particles with $|\eta| < 2.5$

ATLAS detector is excellent tool for study the azimuthal anisotropy:

$\phi$ - full azimuthal acceptance

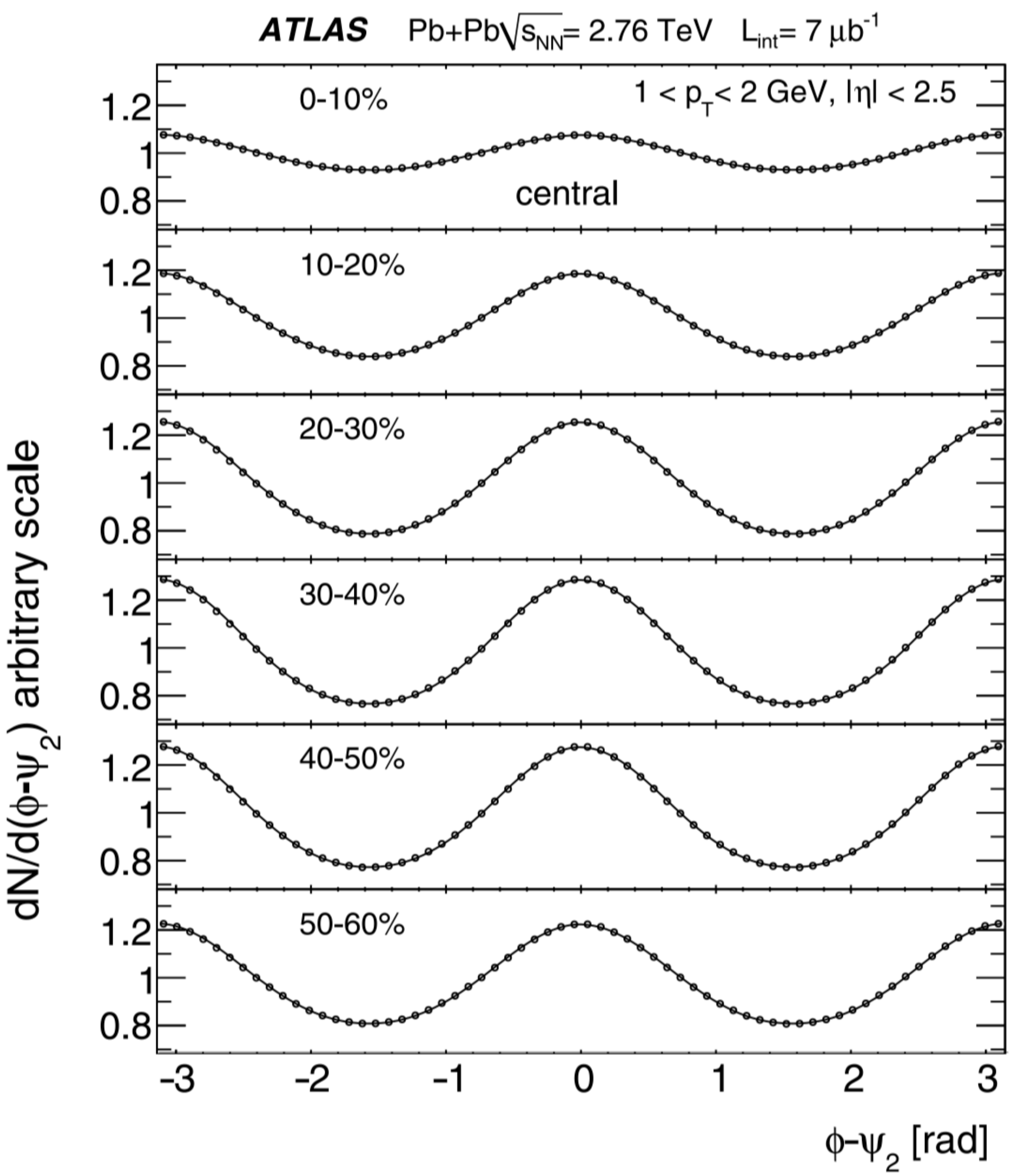
$\eta$ - broad pseudo rapidity coverage $$\eta = -\ln\left[\tan(\frac{\theta}{2})\right]$$

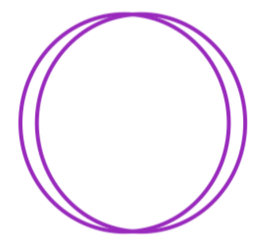
$p_T$ - transverse momentum $$p_\mathrm{T} = \sqrt{p_x^2 + p_y^2}$$

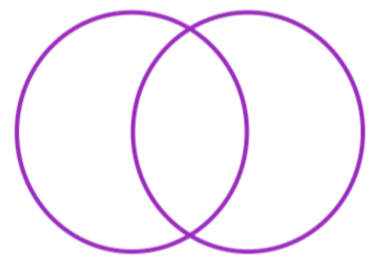
# Collision centrality

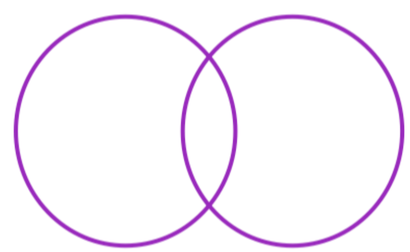


PLB 707 330 (2012)







## Central collision:

- Small distance between the centres of the nuclei
- Large number of participants
- Many charged particles produced (high multiplicity)

## Peripheral collision:

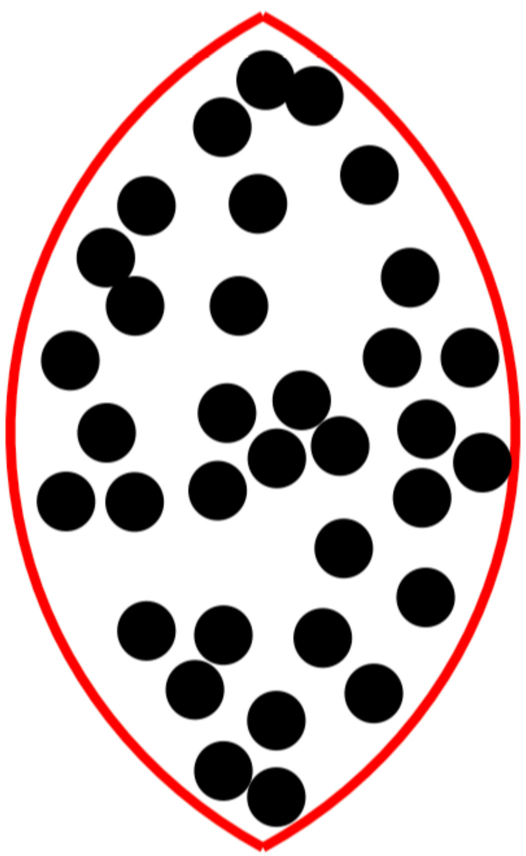
- Large distance between the centres of the nuclei
- Small number of participants
- Few charged particles produced (small multiplicity)

# Role of interactions



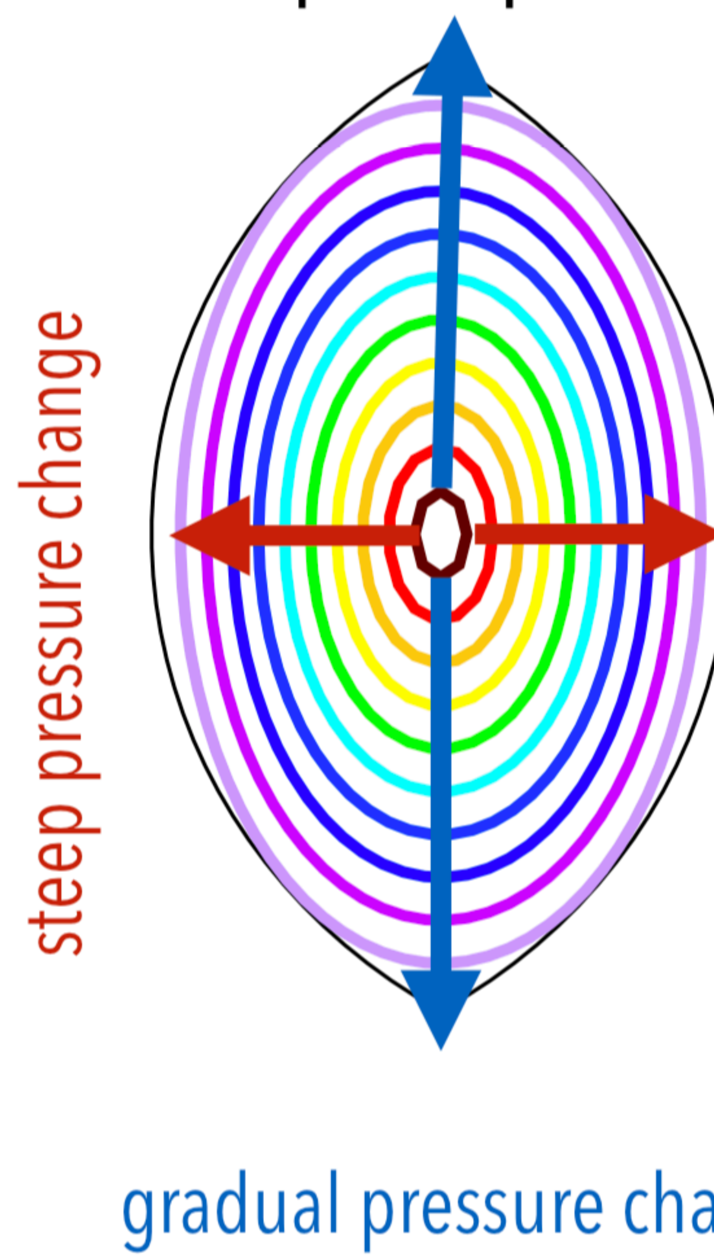
**gas**: minimal interactions

isotropic expansion



**fluid**: lots of interactions

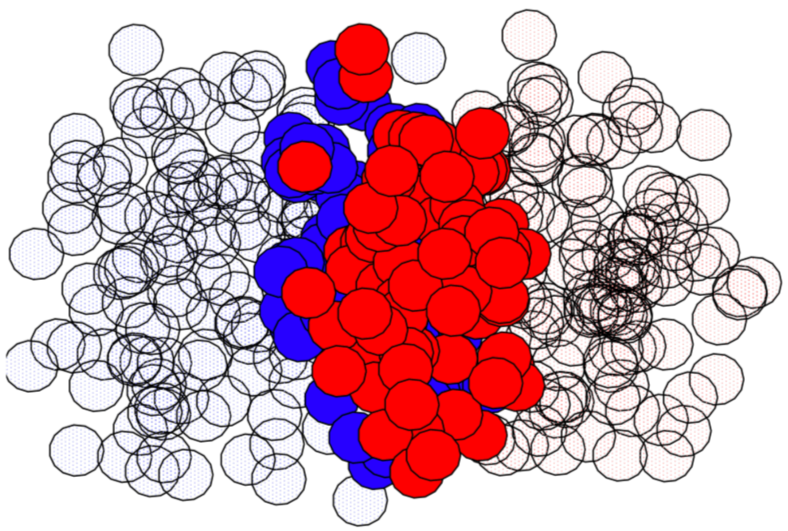
anisotropic expansion

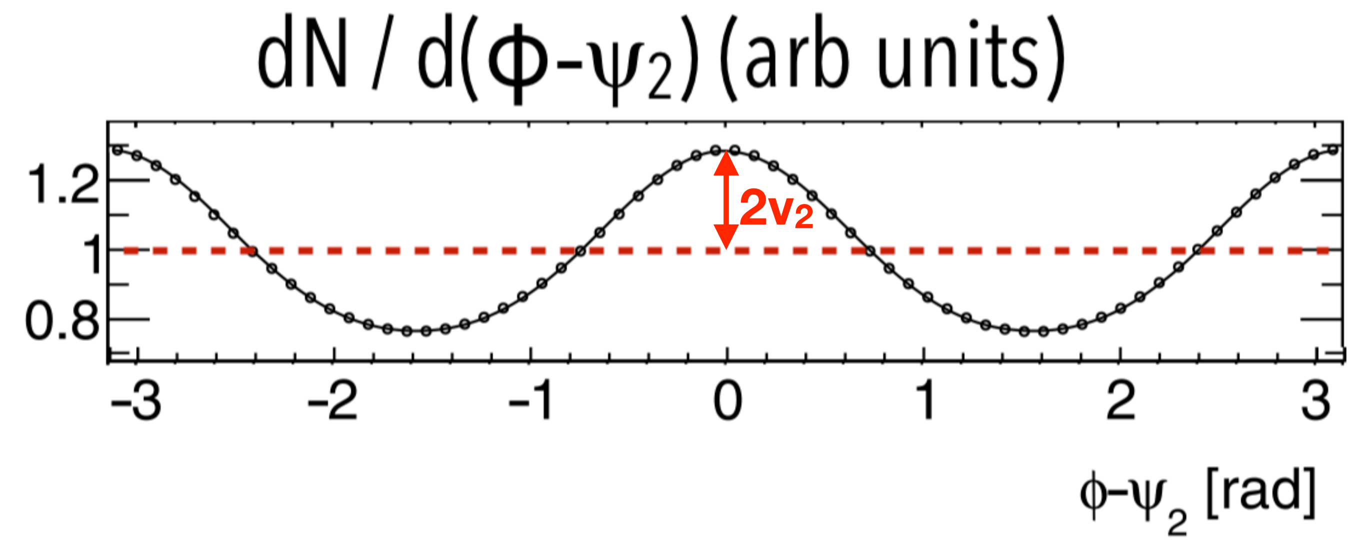


# Hydrodynamic modeling



eccentricity in initial state ⟶ anisotropy in final state



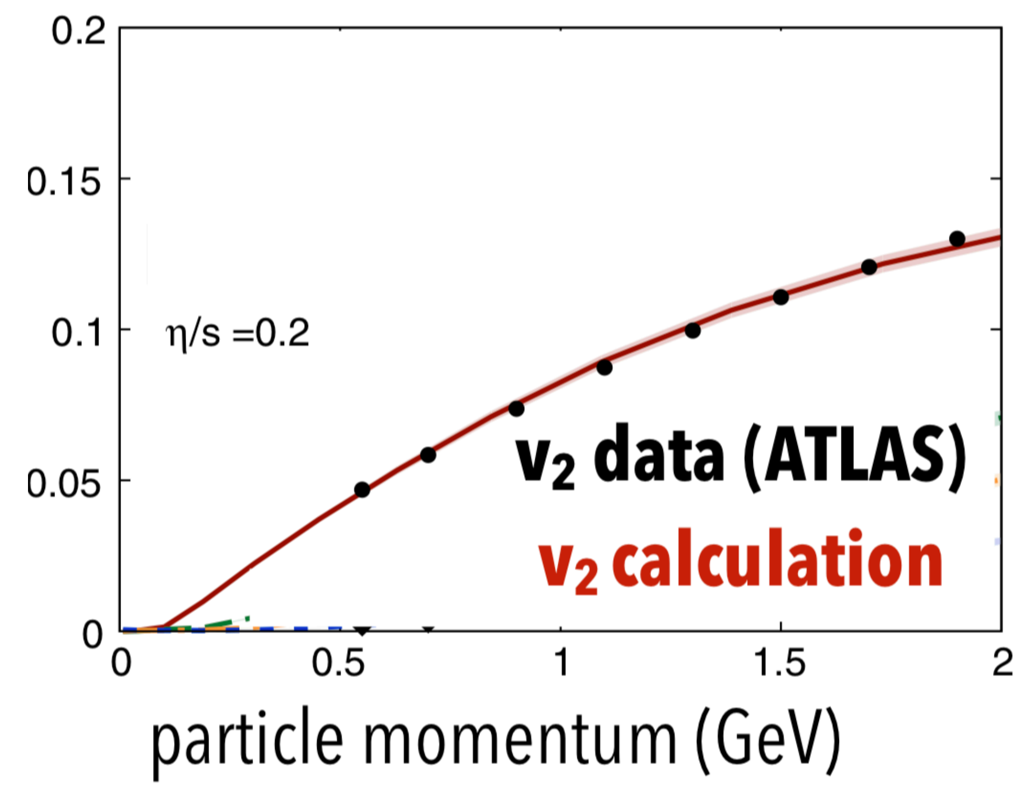



$$\frac{dN}{d\phi} \propto 1 + 2v_2 \cos[2(\phi - \Psi_2)]$$

$v_2$ → amplitude of modulation

increasing viscosity reduces the observed $v_2$ values

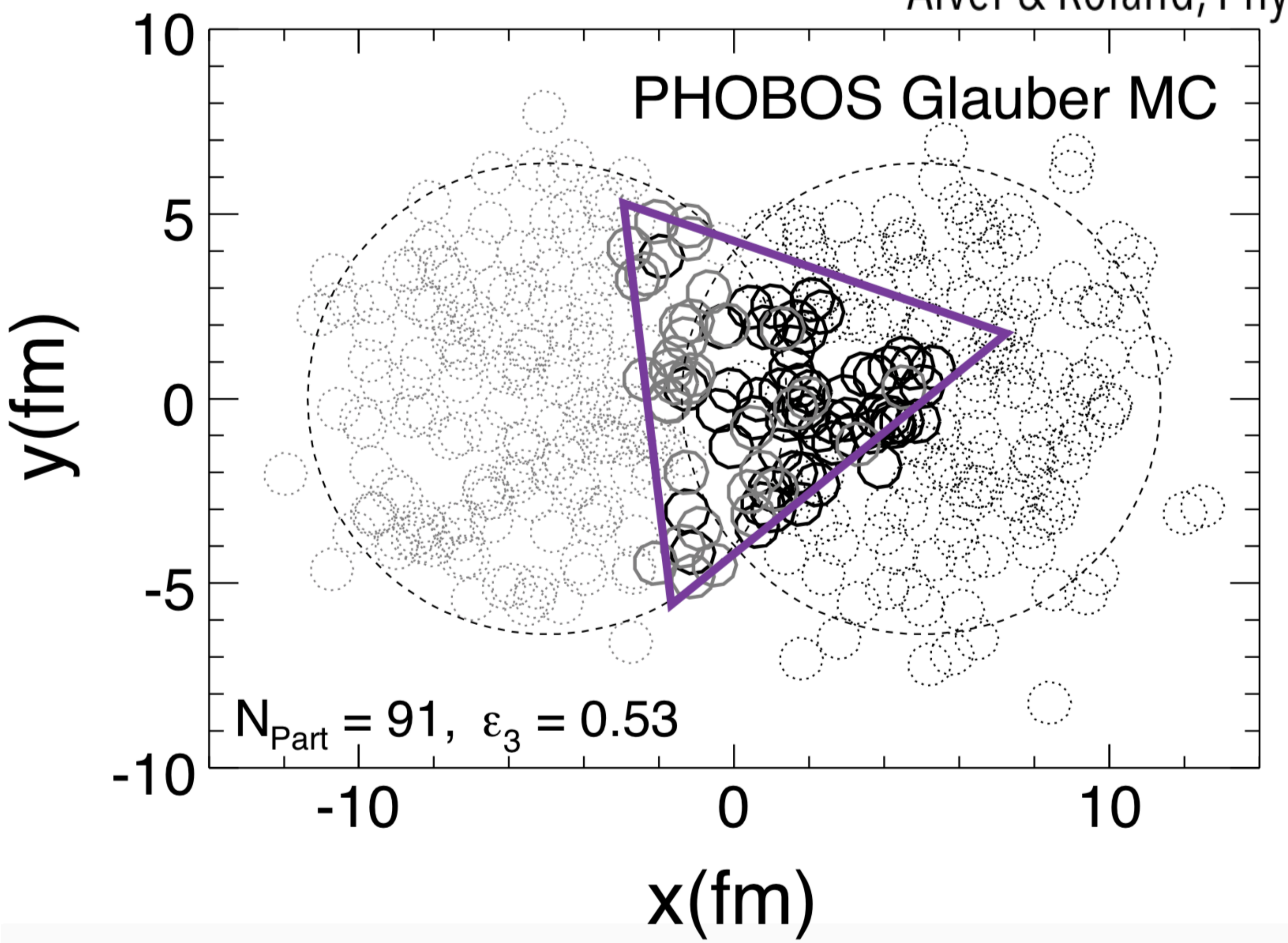
Gale, et al PRL 110 012302



# Role of fluctuations



Alver & Roland, Phys.Rev. C81 (2010) 054905

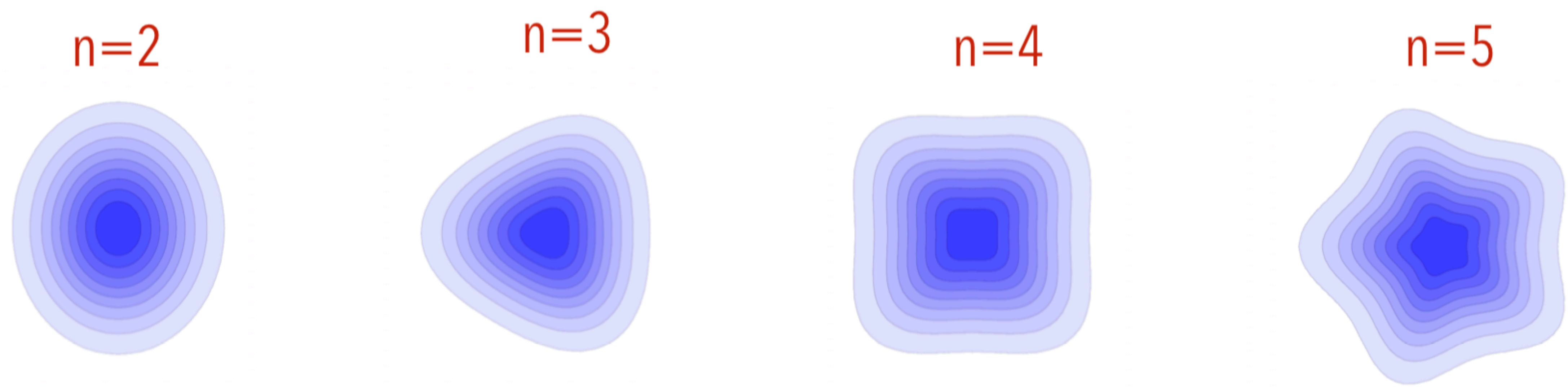



fluctuations in the nucleon position can create any shape of the initial nucleon

→ not just $v_2$, but $v_3$, $v_4$, … can be measured

# Role of fluctuations





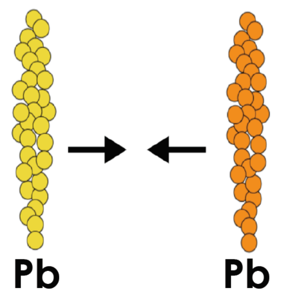

Particle distribution can be written as:

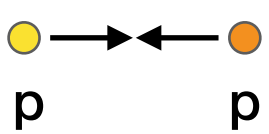
$$\frac{dN}{d\phi} \propto 1 + 2v_2\cos[2(\phi - \Psi_2)] + 2v_3\cos[3(\phi - \Psi_3)] + \ldots$$

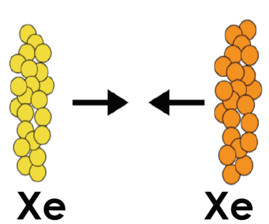
**flow harmonics**

- Elliptic flow, $v_2$, describes the strength of the azimuthal anisotropy related to the elliptical shape of the collision zone
- Higher order harmonics, $v_3$, $v_4$, … → generated by fluctuations
- $v_n$ is increasingly damped by viscosity with larger n
- Simultaneous measurements of $v_2$, $v_3$, $v_4$, … provide better understanding of initial states and medium properties

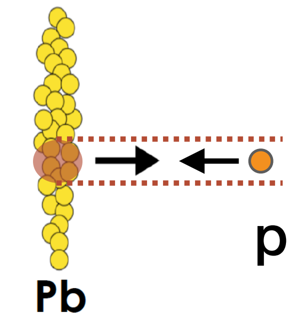
# ATLAS heavy-ion datasets

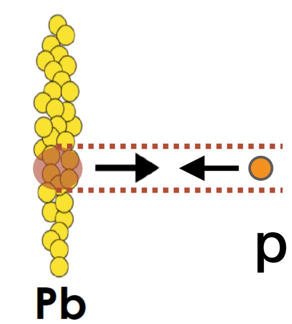


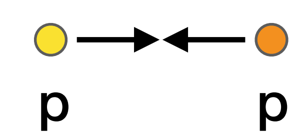



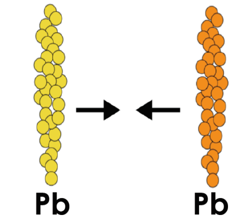

| System | Year | $\sqrt{s_{\mathrm{NN}}}$ [TeV] | $\mathrm{L_{int}}$ |
|---|---|---|---|
| Pb+Pb | 2010 | 2.76 | 9 $\mu$b$^{-1}$ |
| Pb+Pb | 2011 | 2.76 | 0.14 nb$^{-1}$ |
| $p$+Pb | 2012 | 5.02 | 1 $\mu$b$^{-1}$ |
| $p$+Pb | 2013 | 5.02 | 29 nb$^{-1}$ |
| $pp$ | 2013 | 2.76 | 4 pb$^{-1}$ |
| $pp$ | 2015, 2016 | 13 | 75 nb$^{-1}$ |
| $pp$ | 2015 | 5.02 | 28 pb$^{-1}$ |
| Pb+Pb | 2015 | 5.02 | 0.49 nb$^{-1}$ |
| $p$+Pb | 2016 | 5.02 | 0.5 nb$^{-1}$ |
| $p$+Pb | 2016 | 8.16 | 180 nb$^{-1}$ |
| $pp$ | 2017 | 13 | 150 pb$^{-1}$ |
| Xe+Xe | 2017 | 5.44 | 3 $\mu$b$^{-1}$ |
| $pp$ | 2017 | 5.02 | 272 pb$^{-1}$ |
| $pp$ | 2018 | 13 | 193 pb$^{-1}$ |
| Pb+Pb | 2018 | 5.02 | 1.75 nb$^{-1}$ |



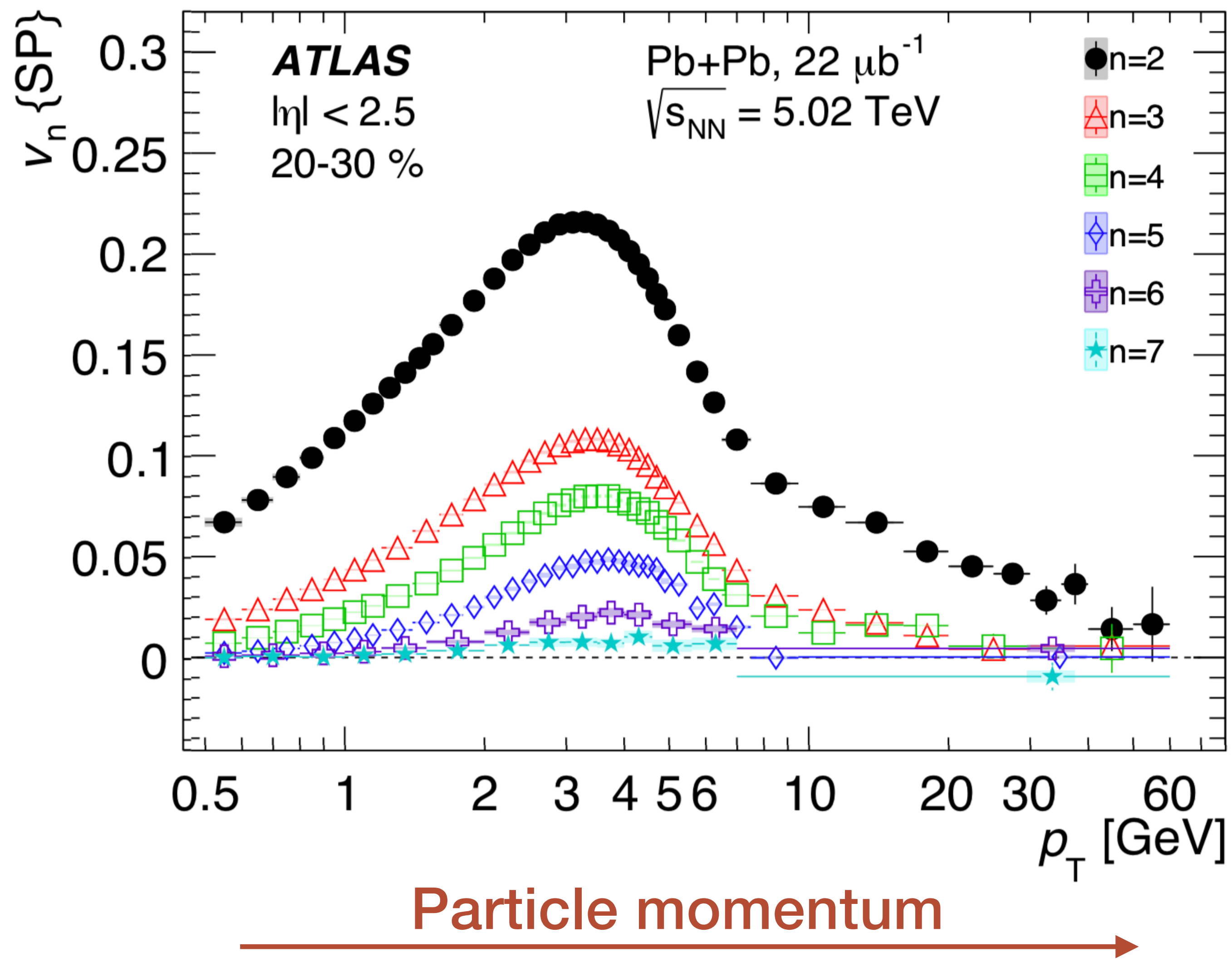



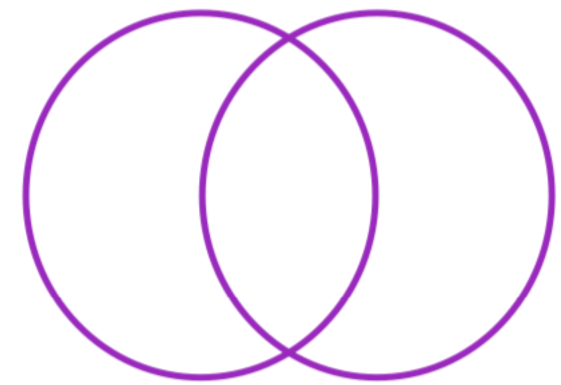



# Flow harmonics in **Pb+Pb** collisions



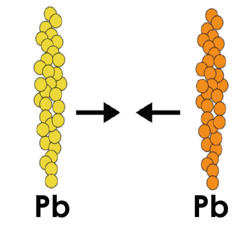

EPJC 78 (2018) 997



- Dominance of overall elliptical shape → $v_2 > v_{n+1}$
- $v_n$ measured up to $p_T$ = 60 GeV → $v_2(p_T)$ positive at highest $p_T$
  → provide information about parton energy loss
- Fluctuations generate $v_3$ and higher

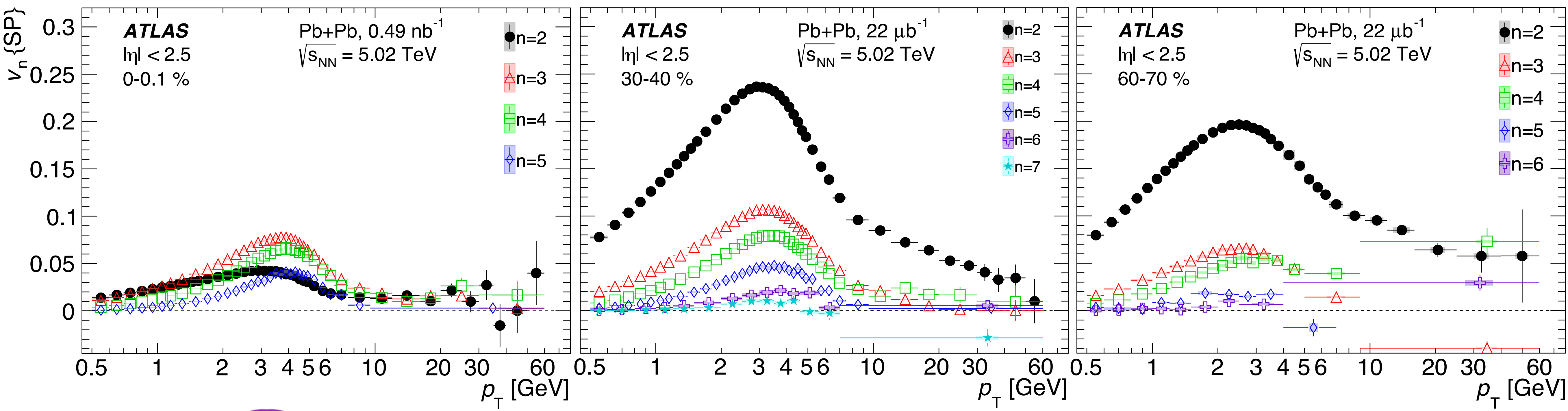
# Flow harmonics in **Pb+Pb** collisions

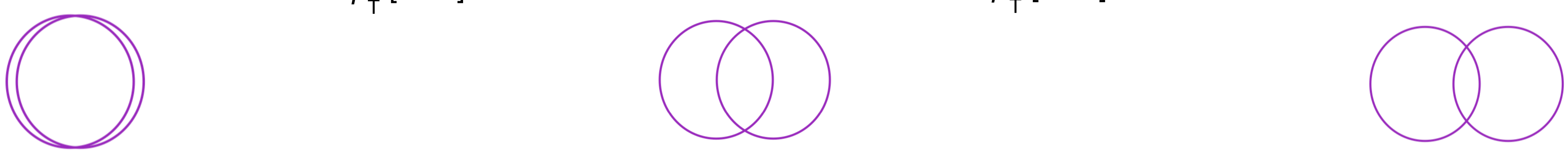





EPJC 78 (2018) 997

## ultra-central | mid-central | peripheral



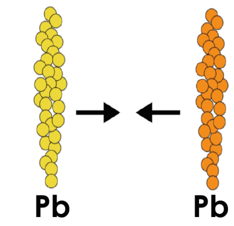
- The elliptic flow ($v_2$) is a dominant source of anisotropy

  → except for the most central collisions

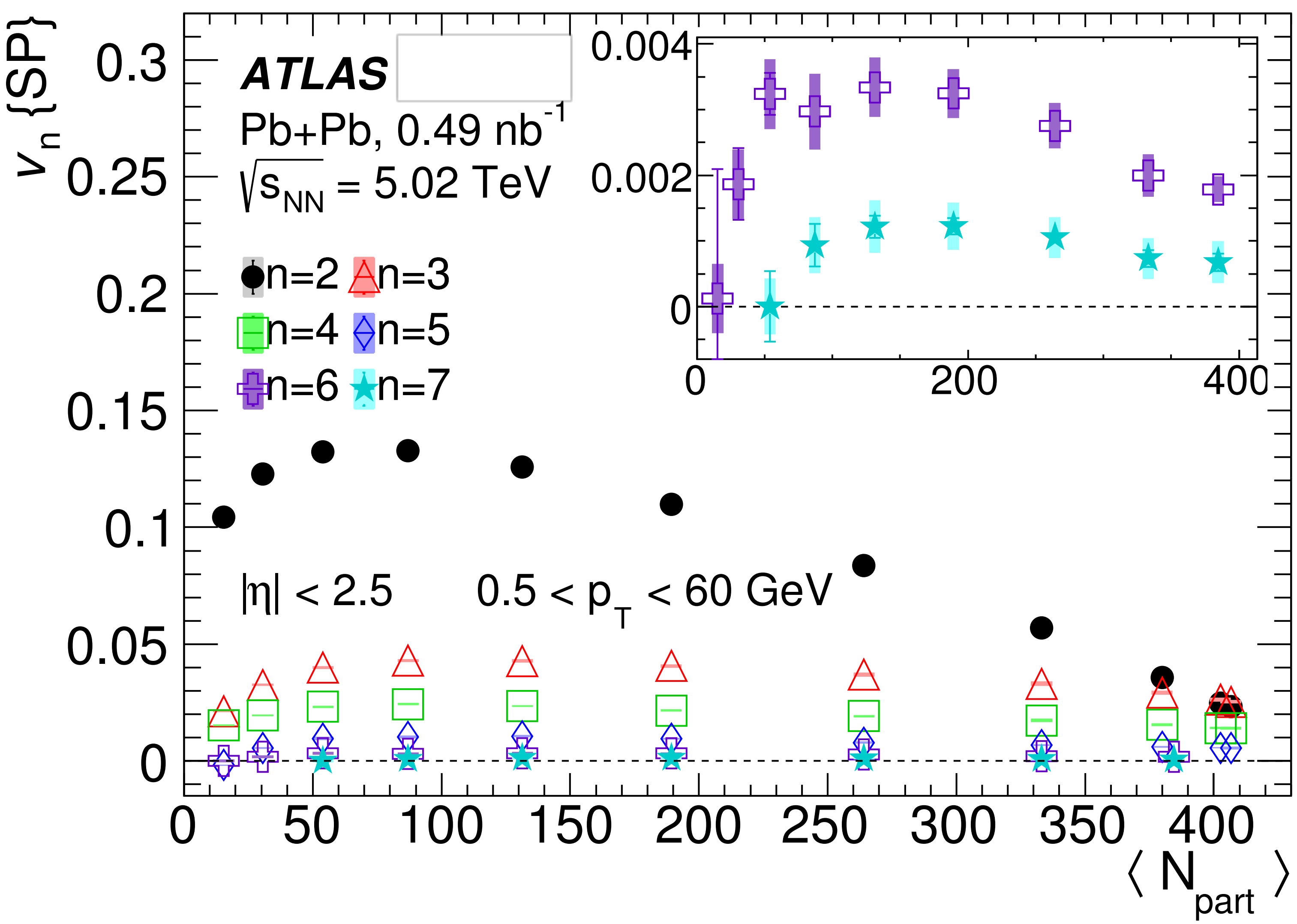
  → the dominant source of observed flow comes from the initial geometry fluctuations

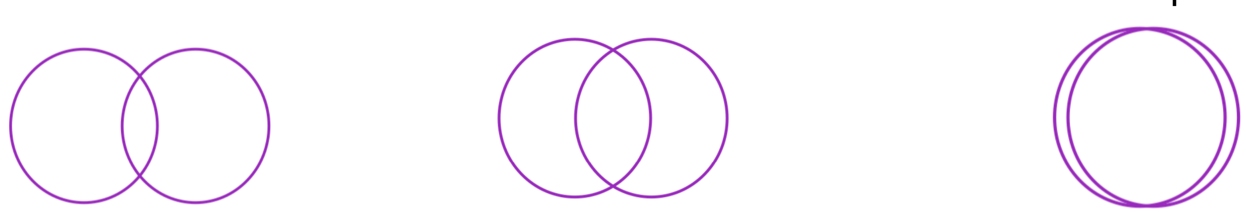
  → $v_3 > v_4 > v_5 \approx v_2$ for the most central collisions at $p_T$ = 3–5 GeV

# Flow harmonics in **Pb+Pb** collisions



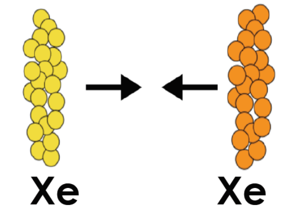

EPJC 78 (2018) 997



- Elliptic flow: strongly dependent on event centrality and largest in mid-central events
- Higher order $v_n$: weak centrality dependence
- The $v_7$ harmonic found to be non-zero for centralities 0-50%

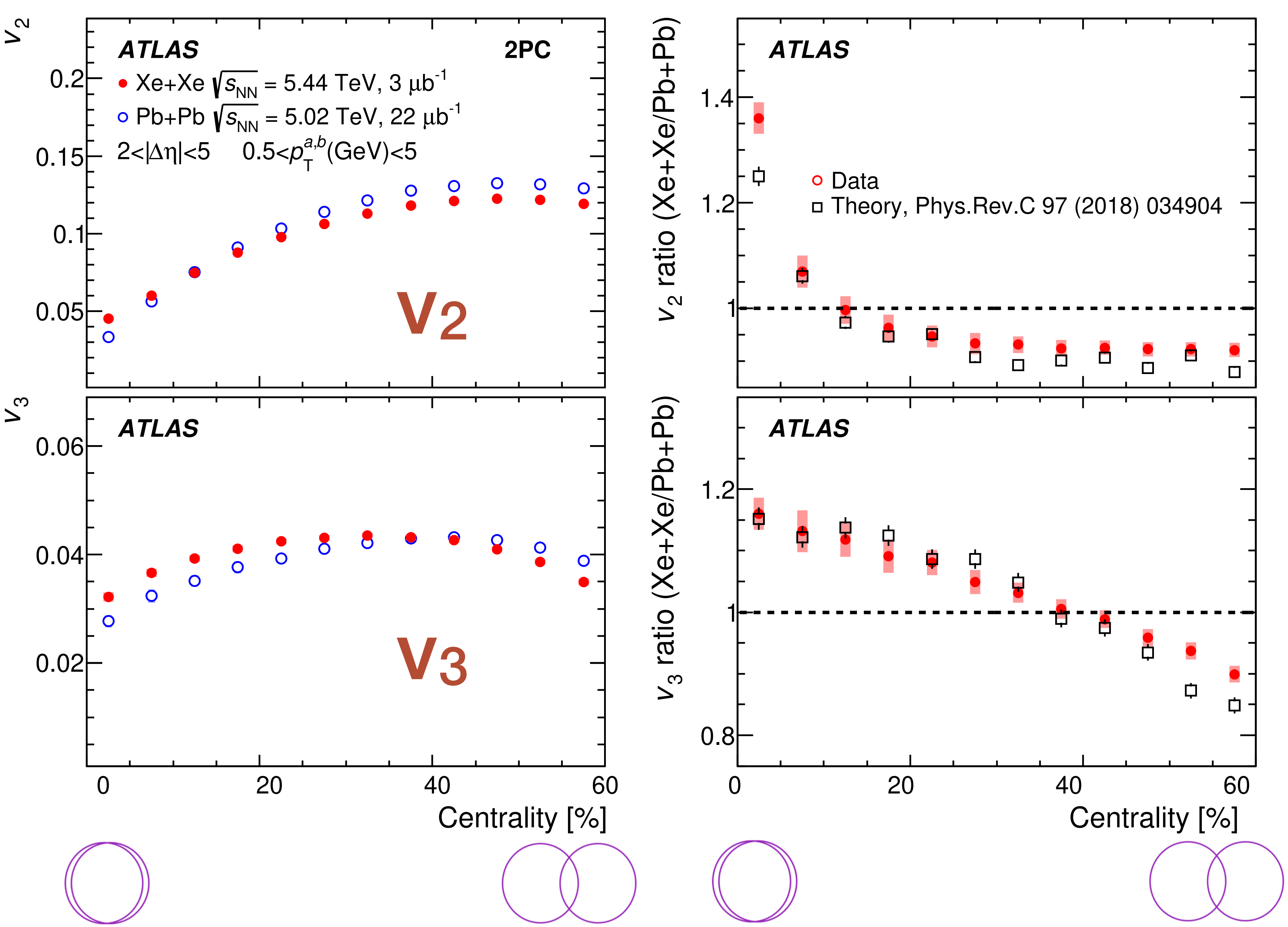
# Flow harmonics **Xe+Xe** collisions



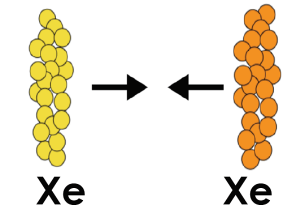

Phys. Rev. C 101, 024906 (2020)

Xe: A = 129
Pb: A = 208

**XeXe/PbPb**



# Flow harmonics **Xe+Xe** collisions

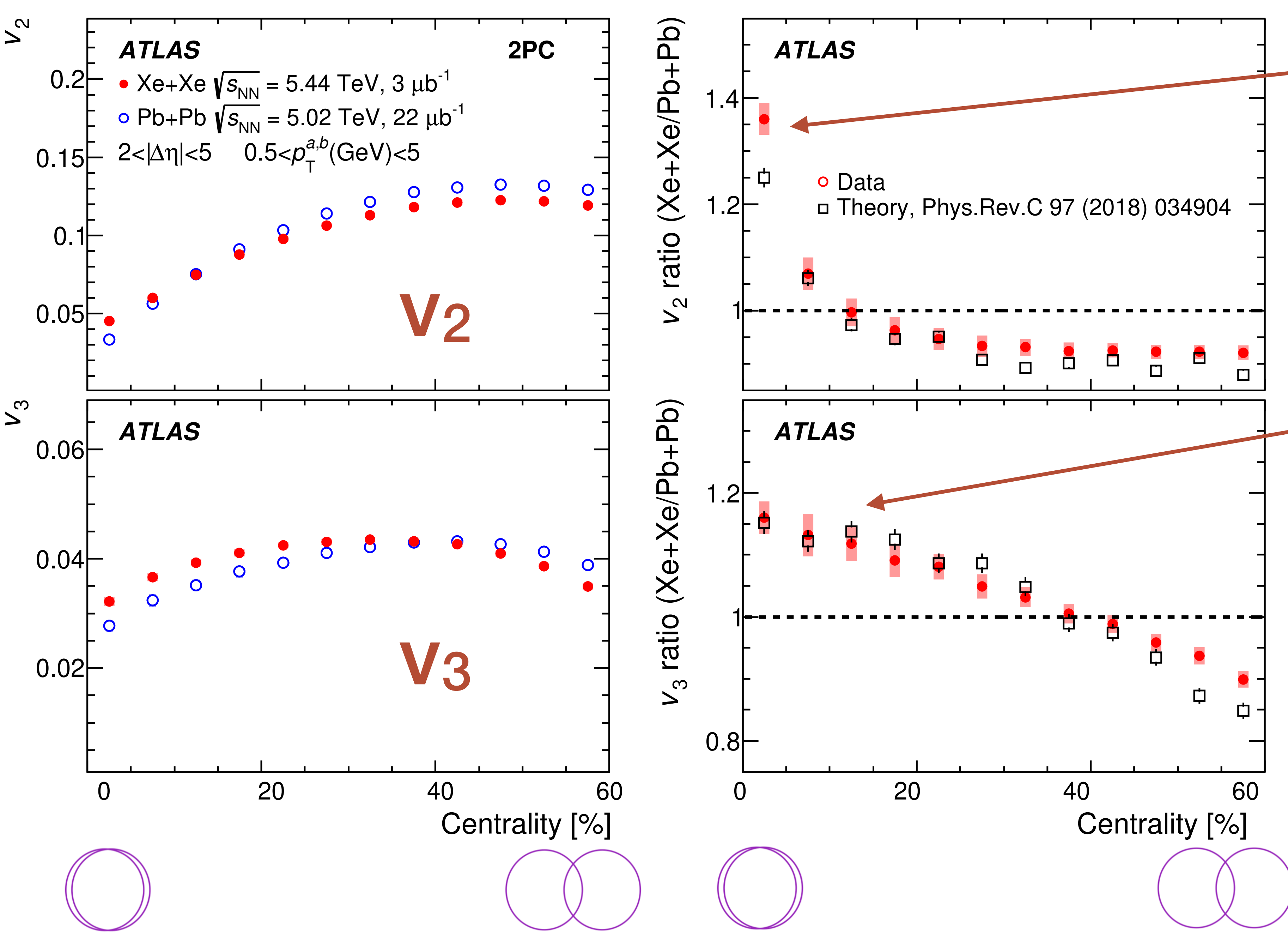



Xe: A = 129
Pb: A = 208

Phys. Rev. C 101, 024906 (2020)

**XeXe has:**

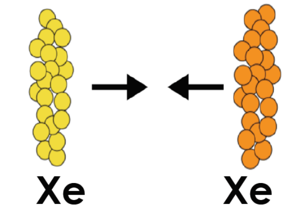
**XeXe/PbPb**




extra $v_2$ in central collisions → more fluctuations

extra $v_3$ → more fluctuations

# Flow harmonics **Xe+Xe** collisions



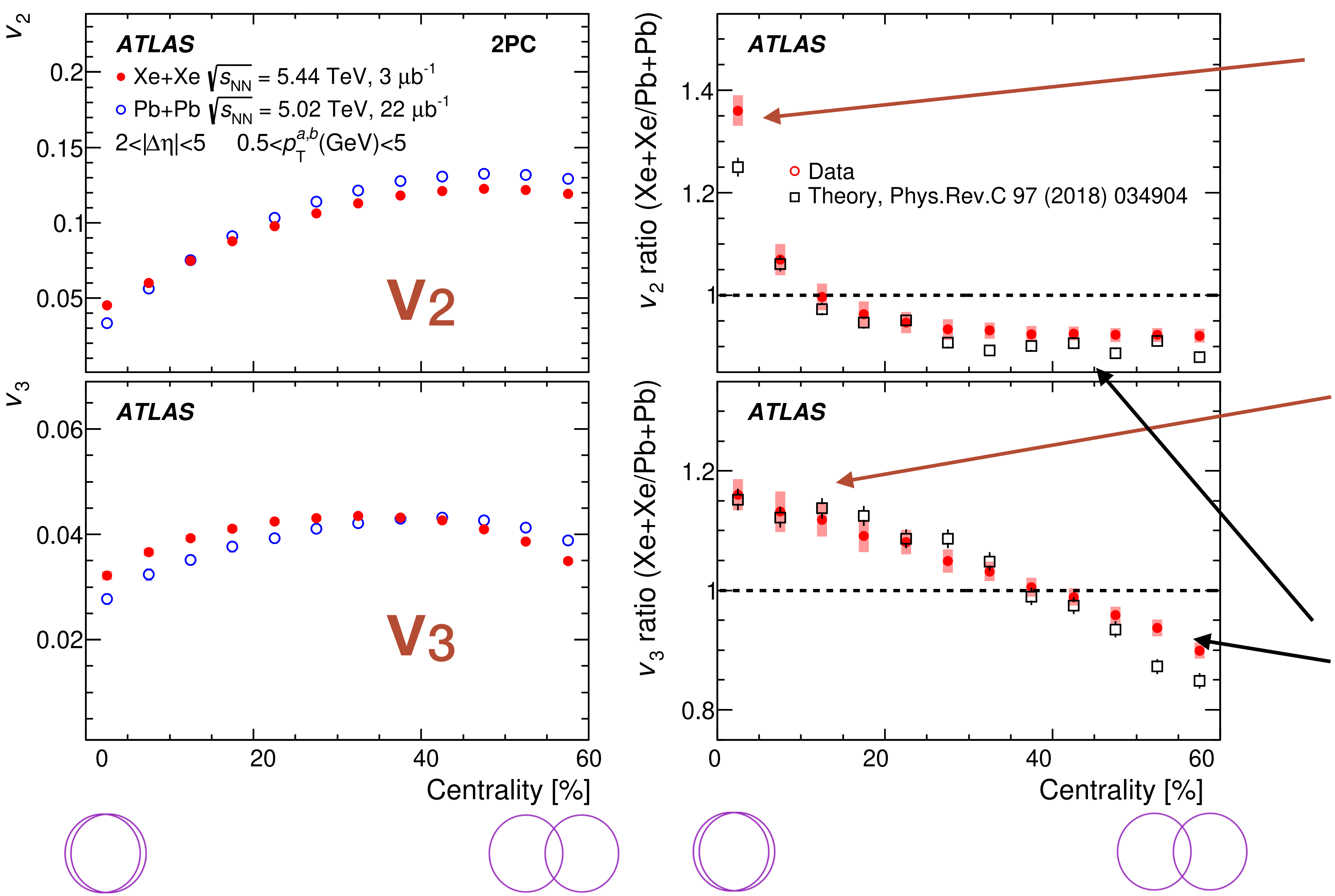



Phys. Rev. C 101, 024906 (2020)

Xe: A = 129
Pb: A = 208

**XeXe has:**

**XeXe/PbPb**



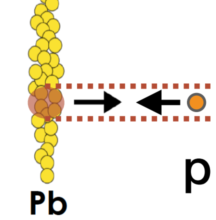

extra $v_2$ in central collisions → more fluctuations

extra $v_3$ → more fluctuations

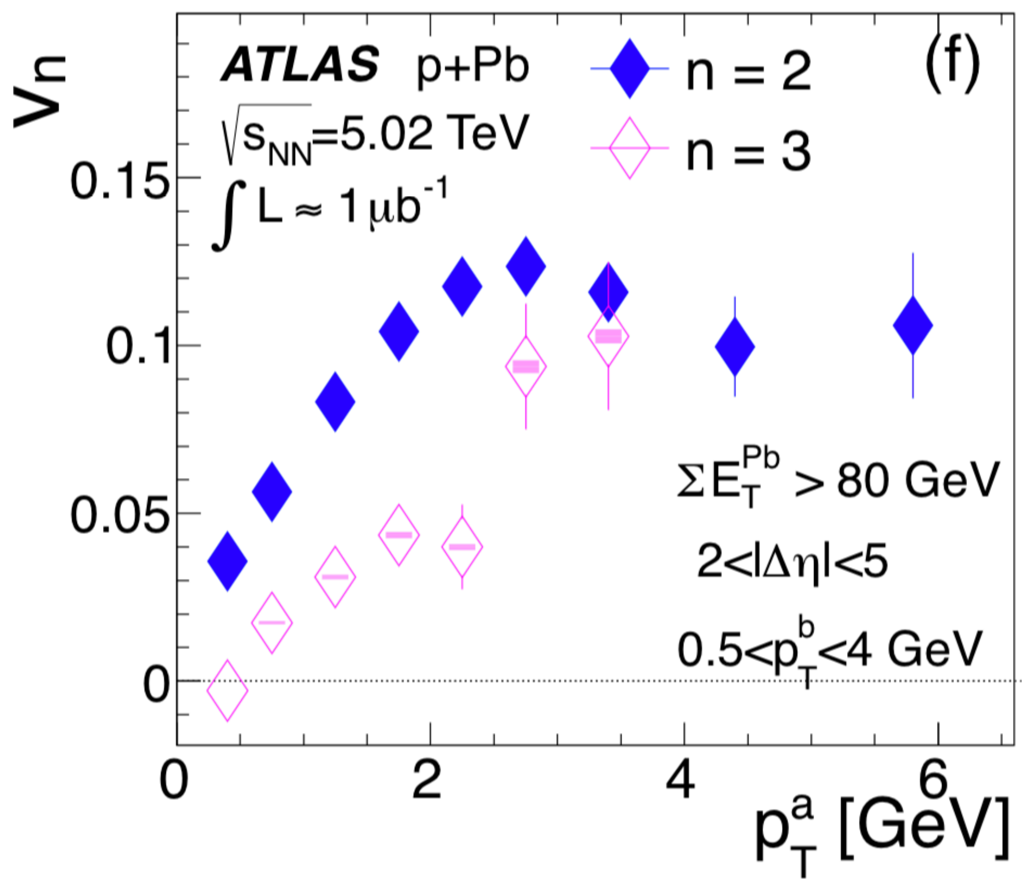
smaller systems: stronger effect of viscosity to reduce $v_n$ values

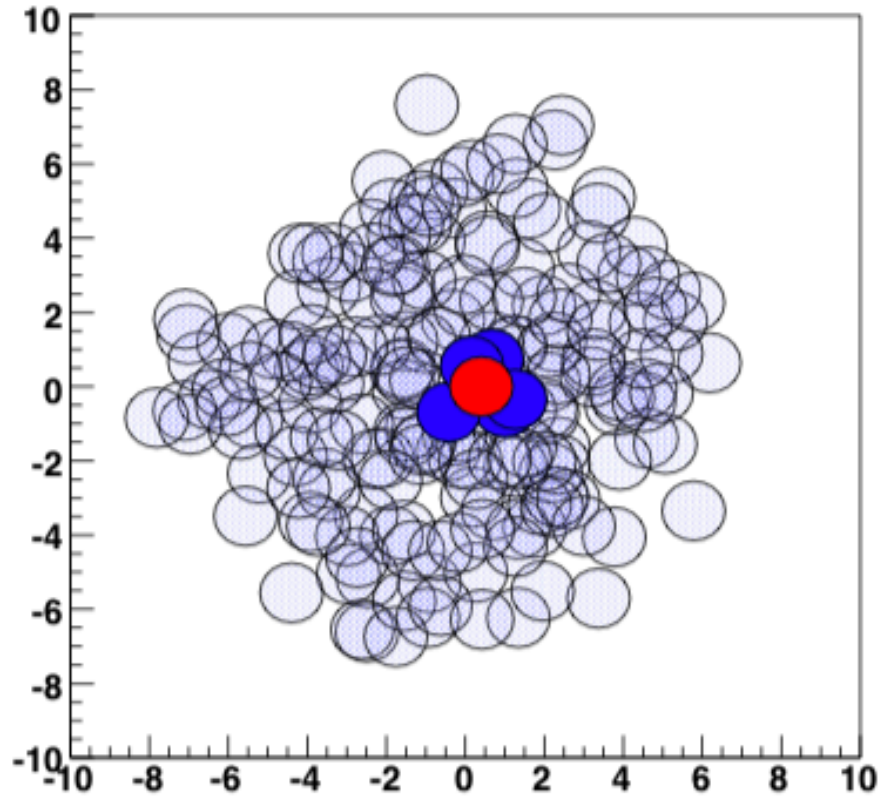
**Consistent with theoretical predictions**

# Smaller system: **p+Pb** collisions



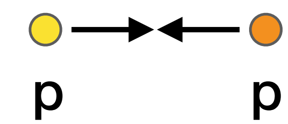

ATLAS PRL 110 102303



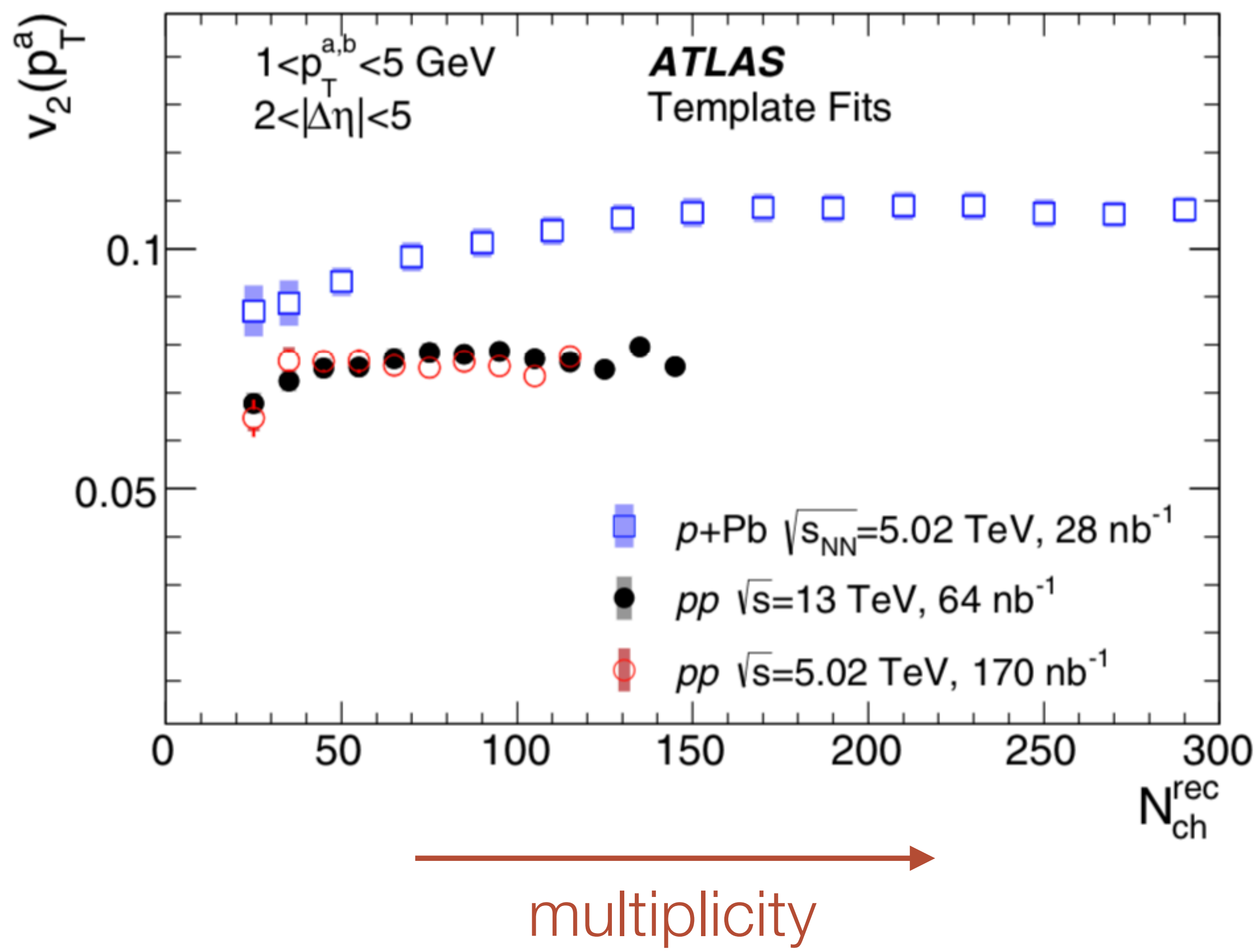



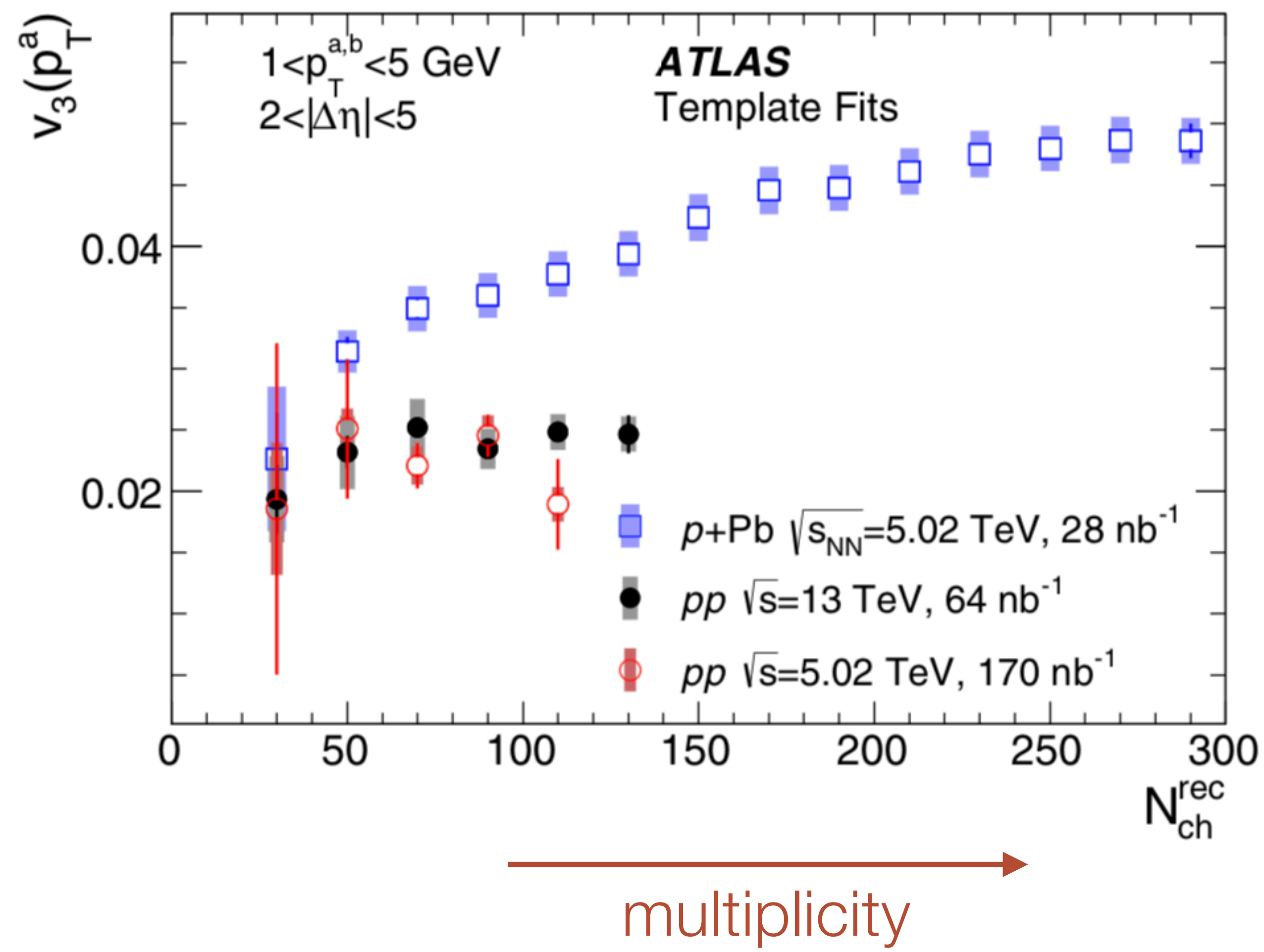
- 2013 surprising result: $v_2$ & $v_3$ measured in p+Pb collisions!
- Very similar to Pb+Pb results
  → are the p+A and A+A $v_n$ related to the same physic?
  → Evidence for QGP formation or something else?

# Smaller system: **p+p** collisions




ATLAS, PRC 96 024908 (2016)



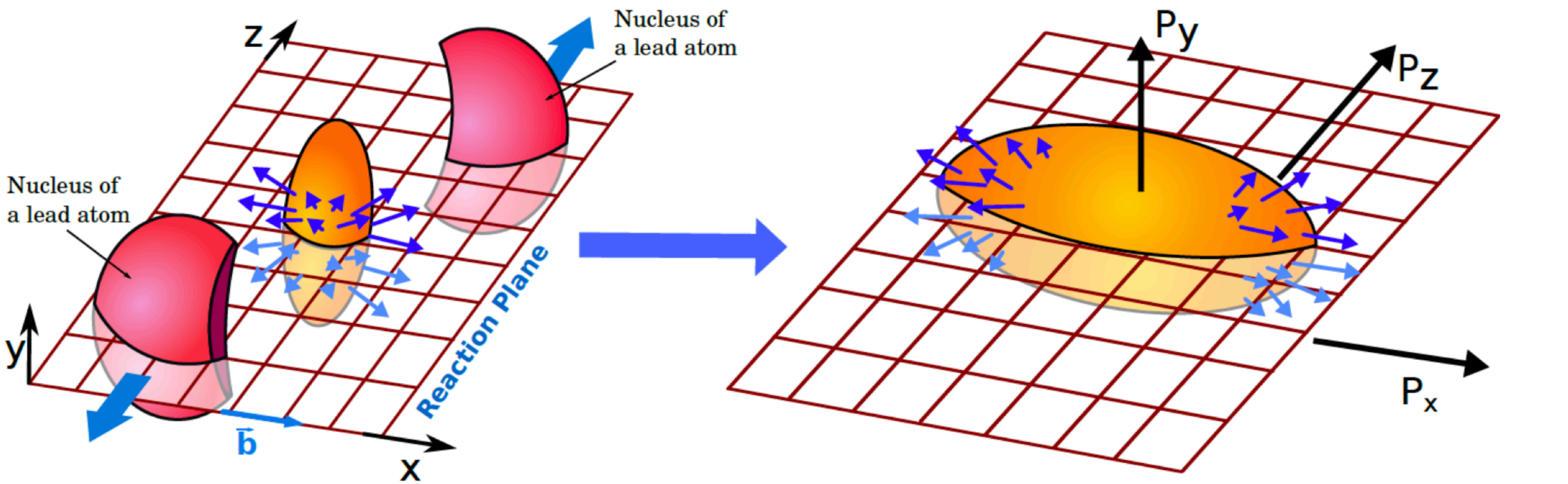

- non-zero $v_2$ & $v_3$ signals!
- evidence for similar $v_n$ signals in **pp collisions** as well
  - QGP in pp collisions?
- this is an area of very active discussions

Weller & Romatschke, PLB 774 351
Mace et al PRL 121 052301
Nagle & Zajc, 1808.01276
M. Strikland, Quark Matter 2018
…
plus many experimental papers

# Flow harmonics and mean $p_T$ correlation

Pressure gradients in QGP lead to azimuthal anisotropy

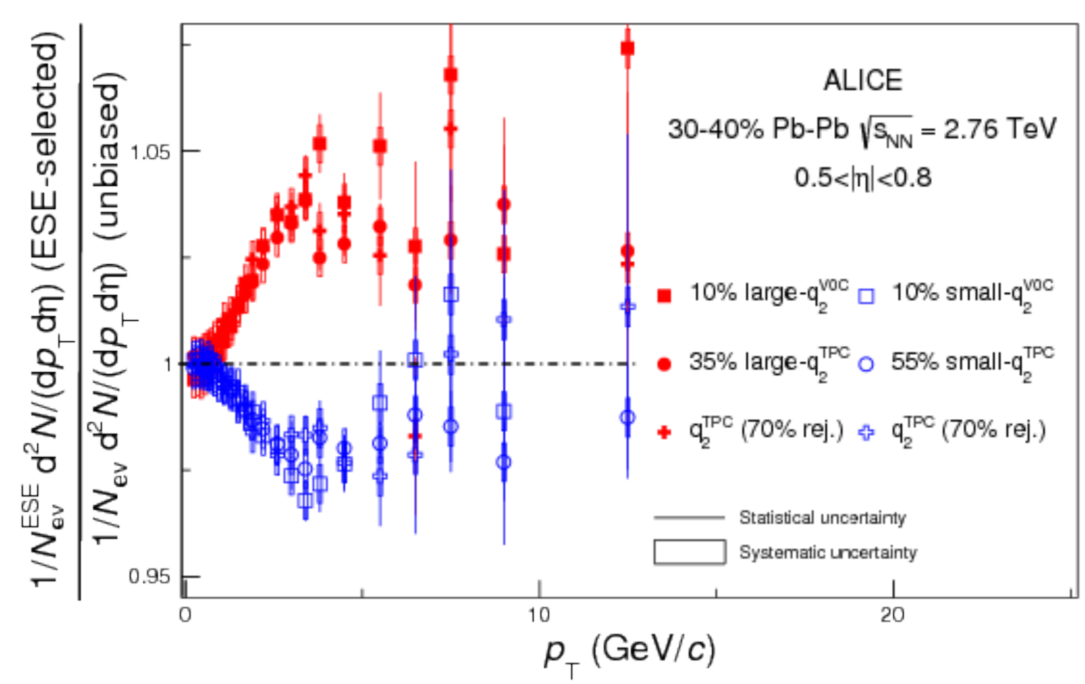
Pressure gradients in QGP lead to variation in the $[p_T]$




As a consequence, its expected that, event-by-event azimuthal flow harmonics should be correlated with the mean $p_T$, $[p_T]$, of the event.

**ALICE measured that the spectra of charged particles become harder when the azimuthal asymmetry in an event increases**

Phys. Rev. C 93 (3 2016) 034916



# Measurement of flow harmonics and mean $p_T$ correlations

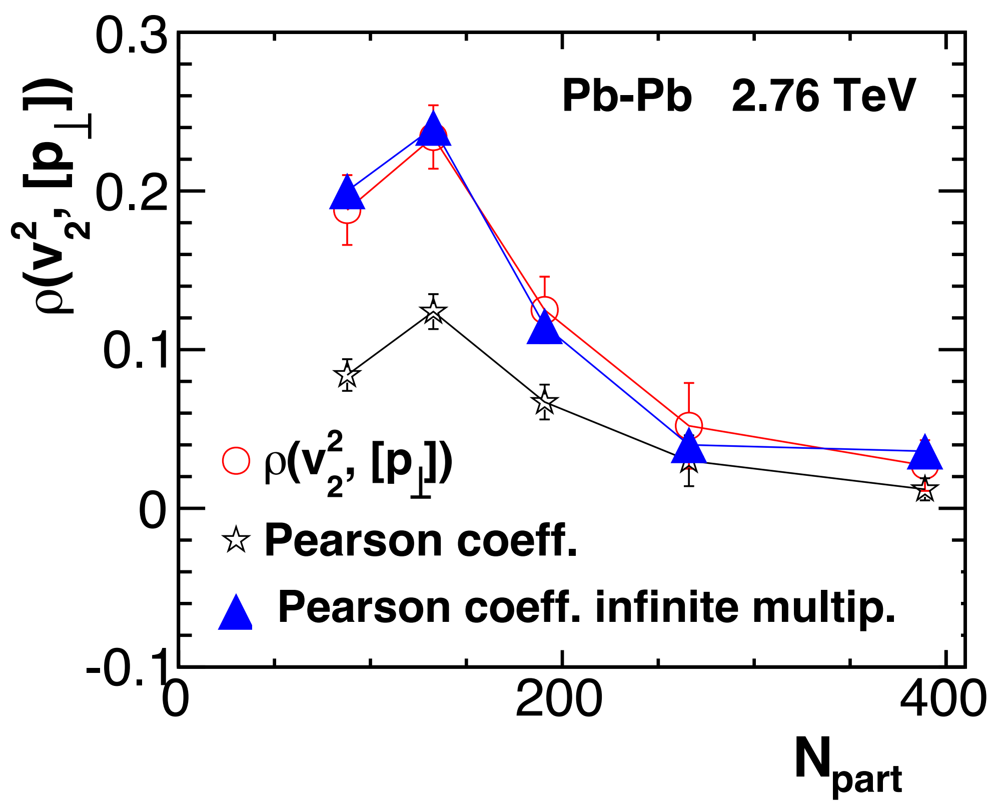
**The new method to measure the relationship is proposed:**

- **study the $v_n$-$[p_T]$ correlations via a modified Pearson correlation coefficient (P. Bozek, PRC 93 (2016) 044908)**

$$R = \frac{cov(v_n\{2\}^2, [p_\mathrm{T}])}{\sqrt{var(v_n\{2\}^2)}\sqrt{var([p_\mathrm{T}])}}$$

$$\rho = \frac{cov(v_n\{2\}^2, [p_\mathrm{T}])}{\sqrt{var(v_n\{2\}^2)_{dyn}}\sqrt{c_k}}$$

- Variances of $[p_T]$ and $v_n\{2\}^2$ contain additional terms due to limited multiplicities
  - replaced by better “dynamical” estimators
- Reproduces R even with limited event multiplicity
  → detector independent measurement



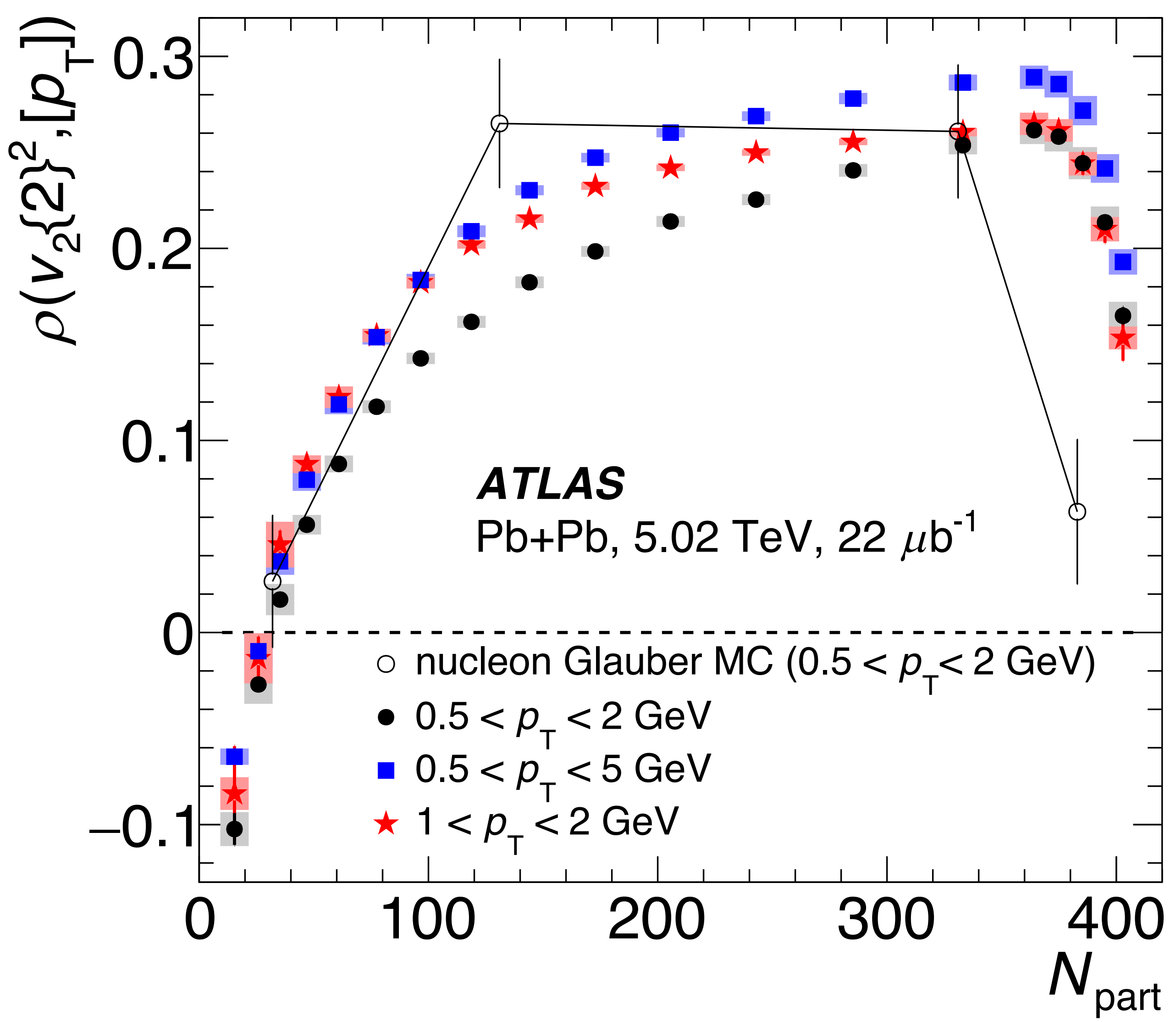

- Questions:

**Is the correlation present & positive or negative? Is it strong? Is it the same for all harmonics? Is it the same in Pb+Pb and p+Pb?**

# $v_2$ – $p_T$ correlations in Pb+Pb collisions

Eur. Phys. J. C 79 (2019) 985

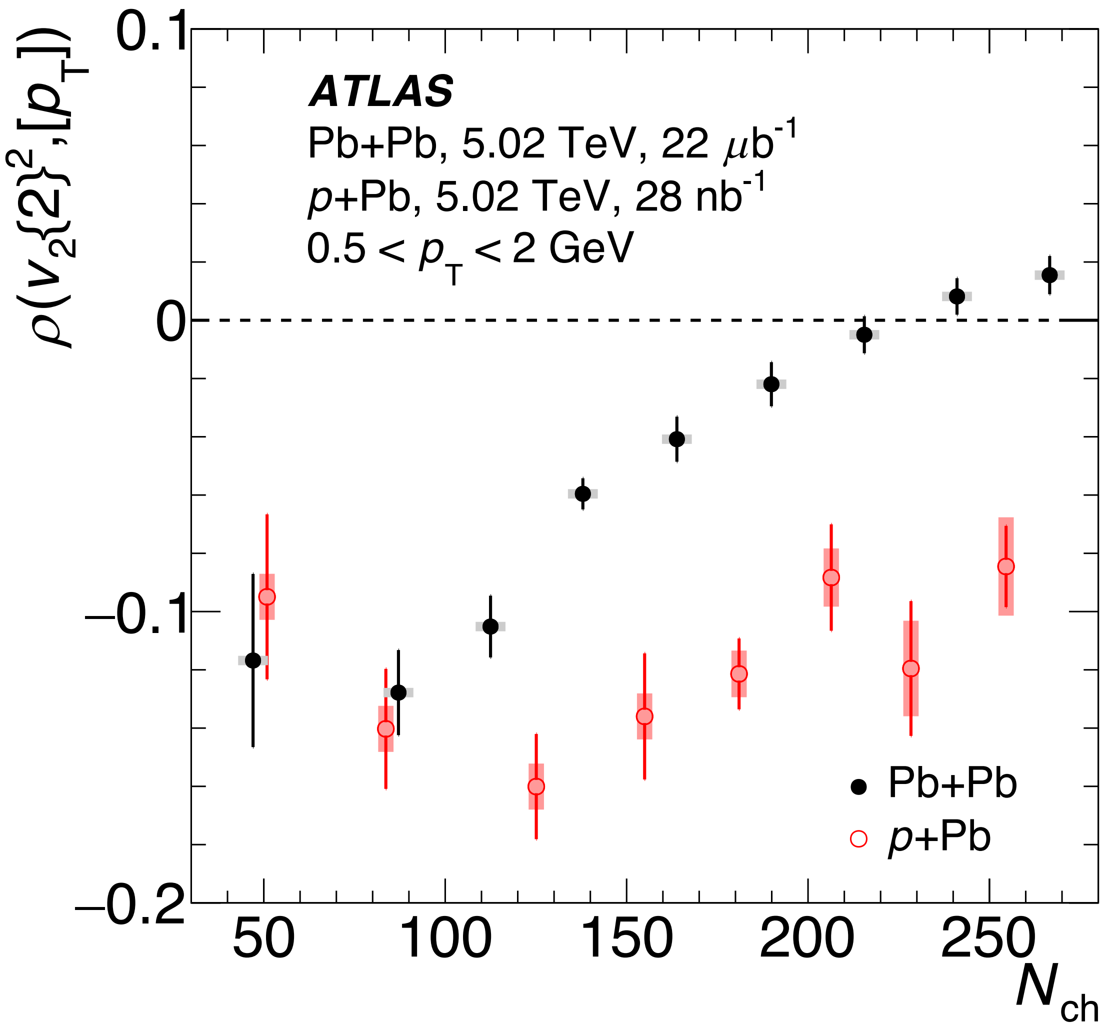
- Negative correlation for $v_2$ in peripheral events
  → related to ecc. ~ 1/r
- Reasonable agreement with the theory prediction
  PR C93 (2016) 044908
- Gentle rise above → stronger hydrodynamic response to initial eccentricities
- Fall in most central events



# $v_n - p_T$ correlations: p+Pb and Pb+Pb comparison



Eur. Phys. J. C 79 (2019) 985




- Correlation in peripheral Pb+Pb and p+Pb events is negative → insight into the small system initial stage
- No geometry driven trend observed in p+Pb compared to a clear effect in Pb+Pb

# Summary

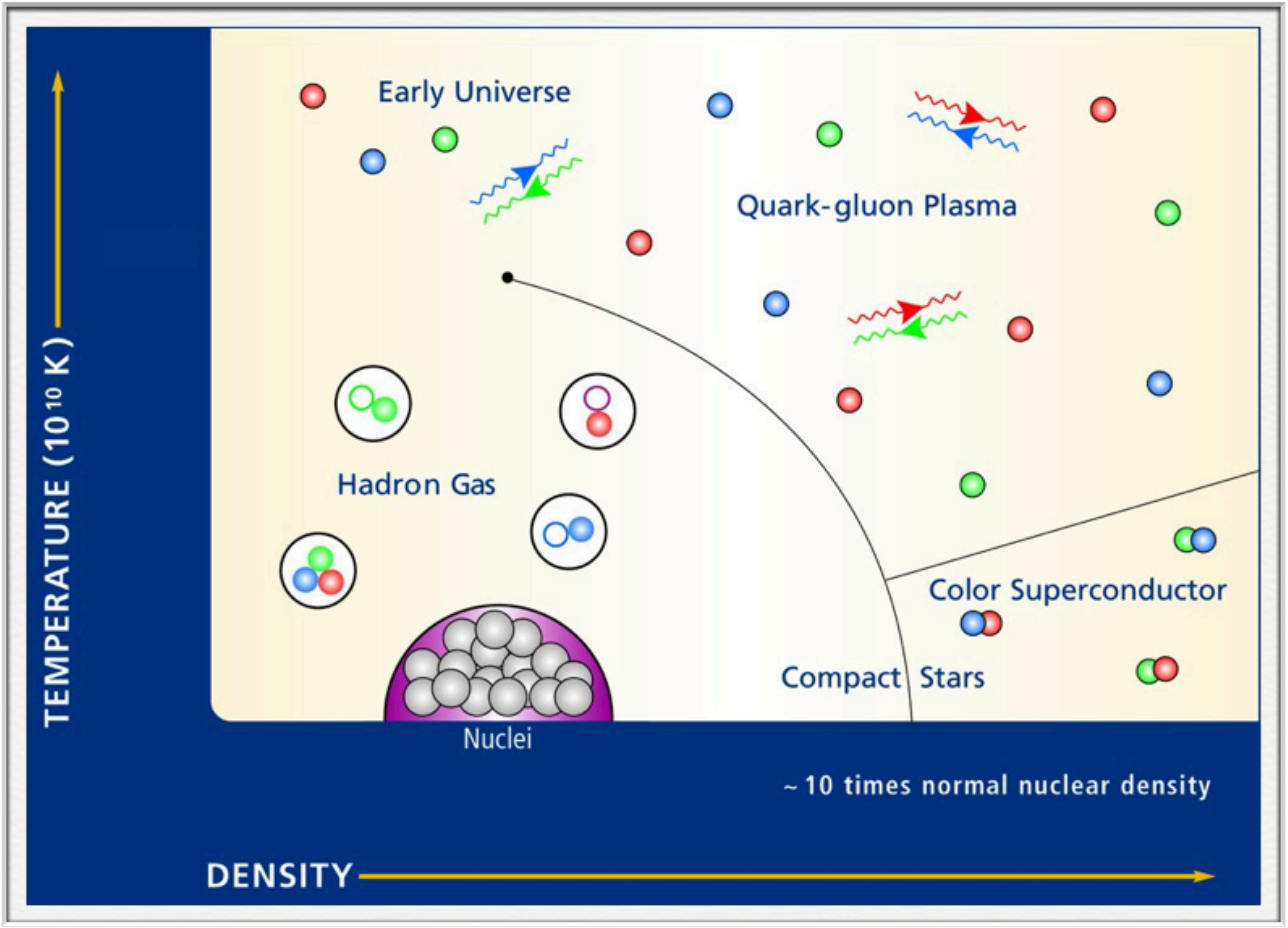


## Thanks to the excellent ATLAS detector and rich datasets:

- **Measured flow harmonics from Pb+Pb to p+p collisions: observation of $v_n$ describable with hydrodynamics**
  - constraining the properties of the quark-gluon plasma
  - similarity of $v_2$ at high $p_T$ in Pb+Pb and p+Pb collisions despite very different system size
- **Performed a comprehensive study of flow in Xe+Xe collisions at 5.44 TeV and compared to Pb+Pb at 5.02 TeV**
  - XeXe provide a way to understand the interplay between geometry and fluctuations
- **ATLAS obtained quantitiative estimate of correlation strenght between $v_n$ and $[p_T]$ in 5.02 TeV Pb+Pb and p+Pb collisions using the modified Pearsons coefficient $\rho$**
  - significant values for all harmonics in mid central Pb+Pb
  - for peripheral Pb+Pb collisions and p+Pb the $v_2$-mean-$p_T$ correlation negative
  - the hydrodynamic model can qualitatively predict that behaviour

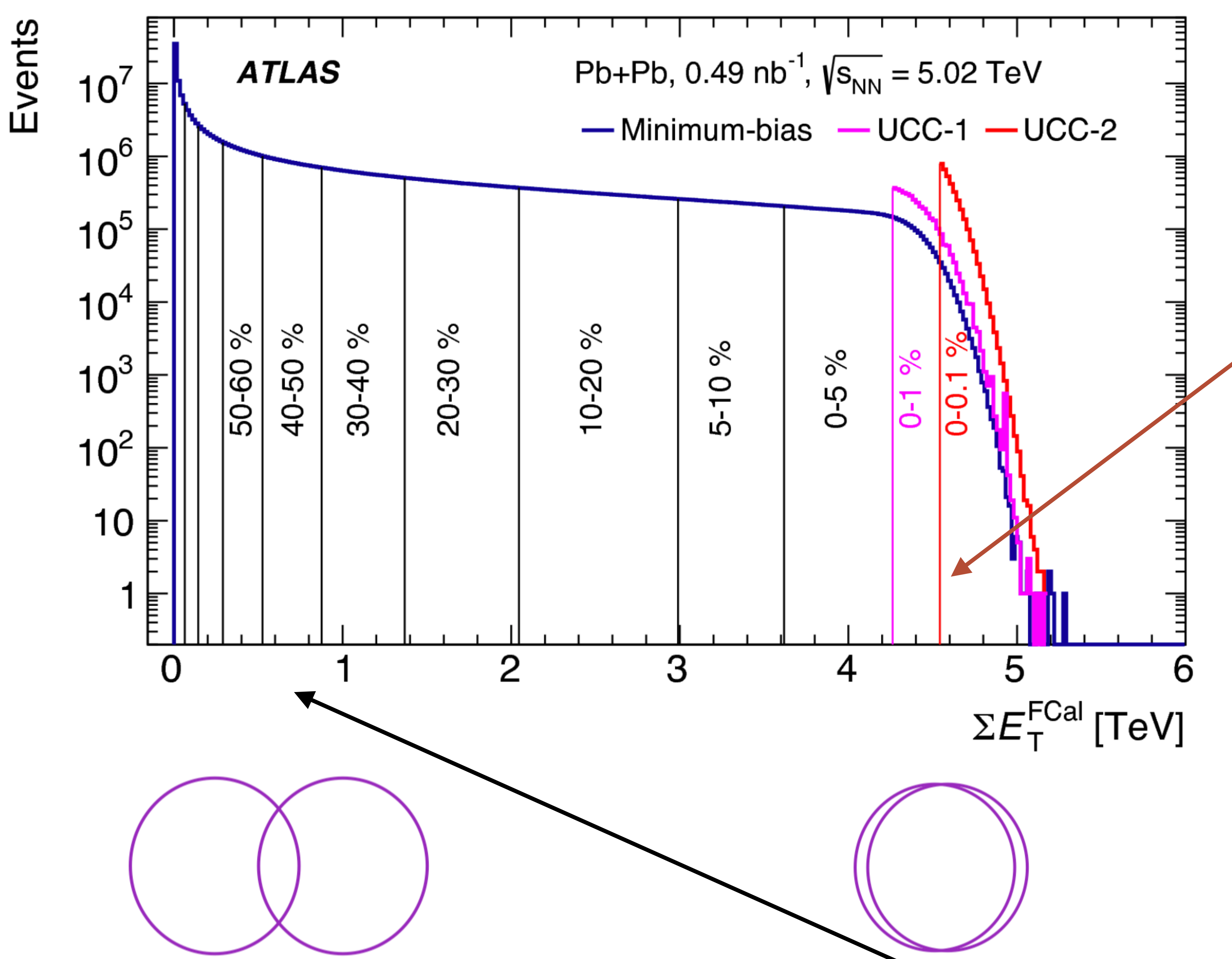
# Phase diagram of nuclear matter





# Collision centrality

PLB 707 330 (2012)




## Central collision:

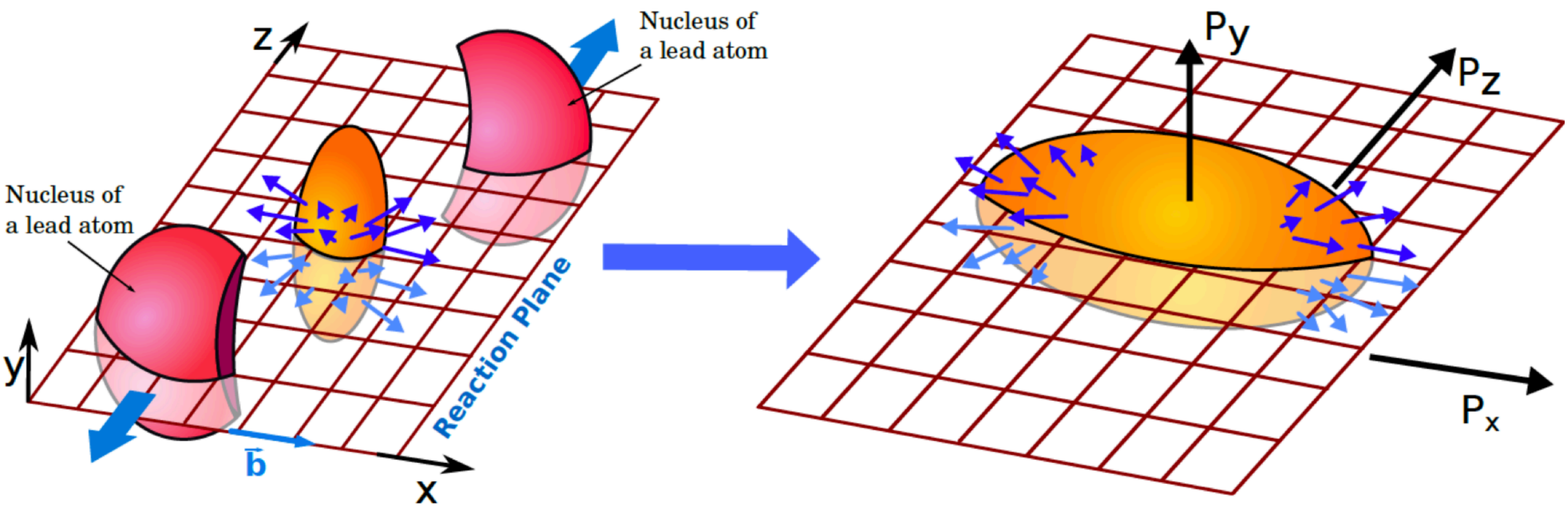
- Small distance between the centres of the nuclei
- Large number of participants
- Many charged particles produced (high multiplicity)
- Large energy deposit in FCal

## Peripheral collision:

- Large distance between the centres of the nuclei
- Small number of participants
- Few charged particles produced (small multiplicity)
- Small energy deposit in FCal

# Azimuthal anisotropy in lead+lead collisions



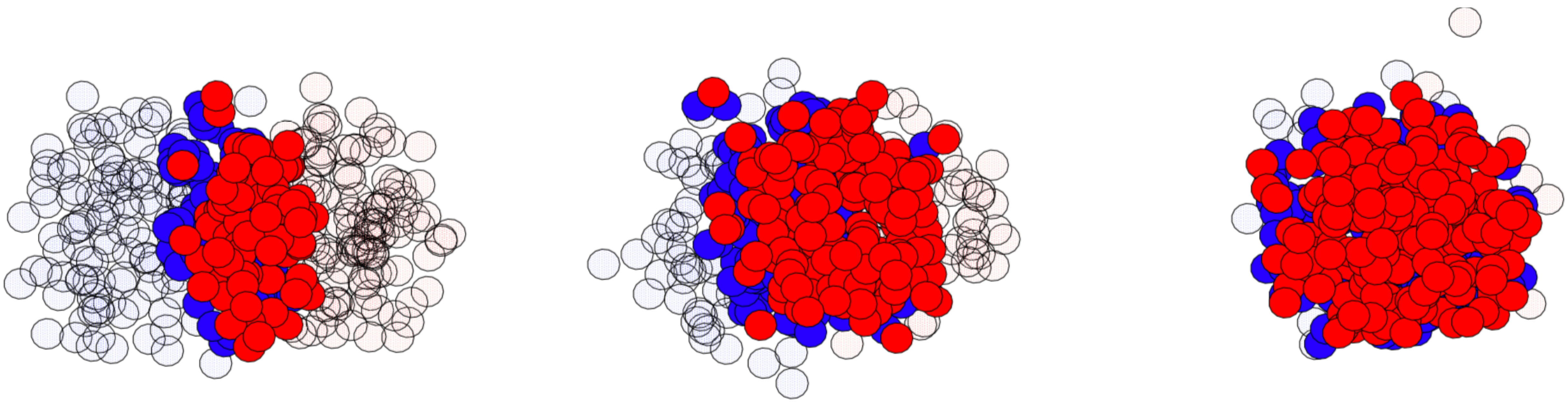



- The initial geometrical asymmetry (x,y) is transferred into a final spatial anisotropy of particles momenta ($p_x$,$p_y$) → in azimuthal angle $\phi$
- Particles are emitted in preferred directions → More, faster particles seen in the reaction plane direction

# Collision geometry



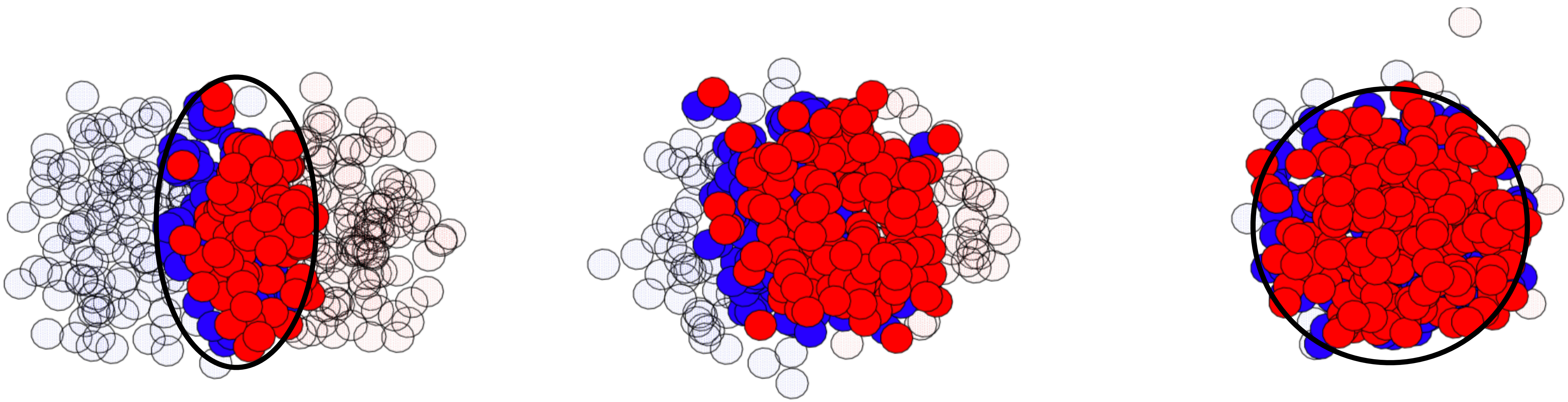
nucleon positions for the colliding nuclei for three different simulated collisions



# Collision geometry



nucleon positions for the colliding nuclei for three different simulated collisions



varying the impact parameter, changes the shape and size of the region where the nuclei overlap