First results from ALICE on anisotropic flow at Run 2 at LHC

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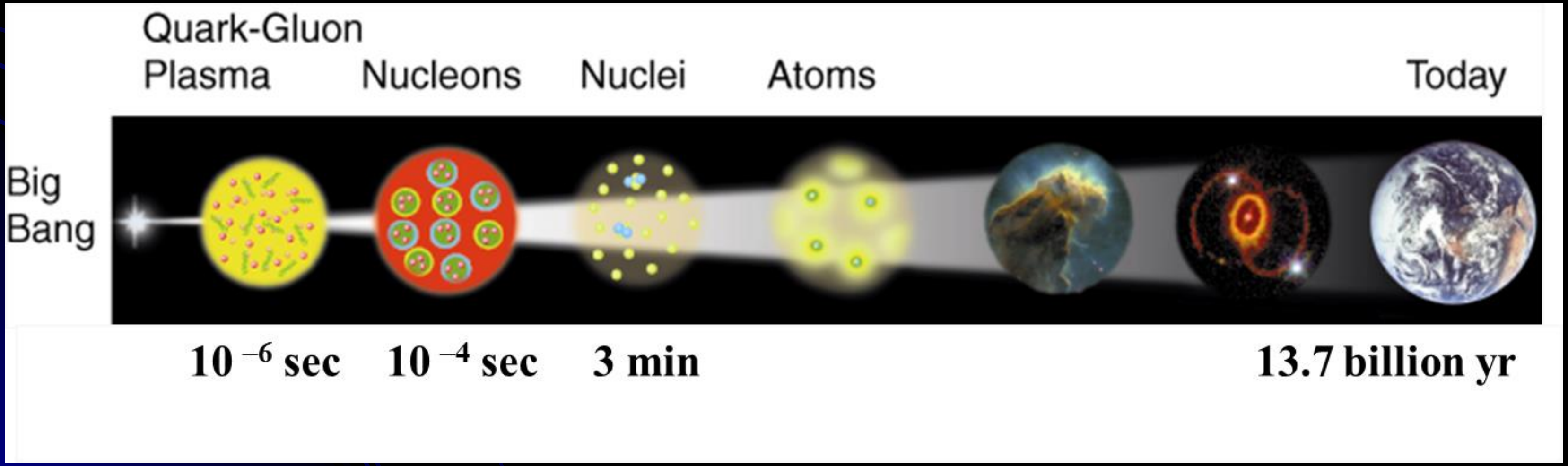
Outline

- Introduction
- Anisotropic flow
- Analysis technique and flow observables
- Theoretical predictions for Run 2
- First results from Run 2
- Outlook

Introduction

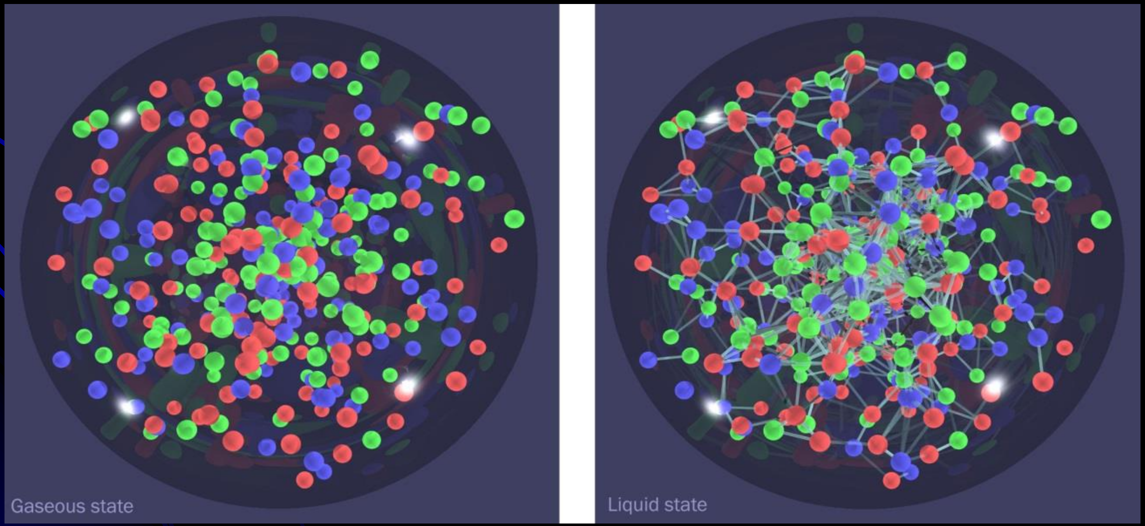
Heavy-ion collisions

- Our mission: To study the properties of nuclear matter under extreme conditions
  - Quantify the properties of the Quark-Gluon Plasma
  - Map the QCD phase diagram
  - Demystify the nature of the strong nuclear force
  - Shed light on the evolution of the early Universe

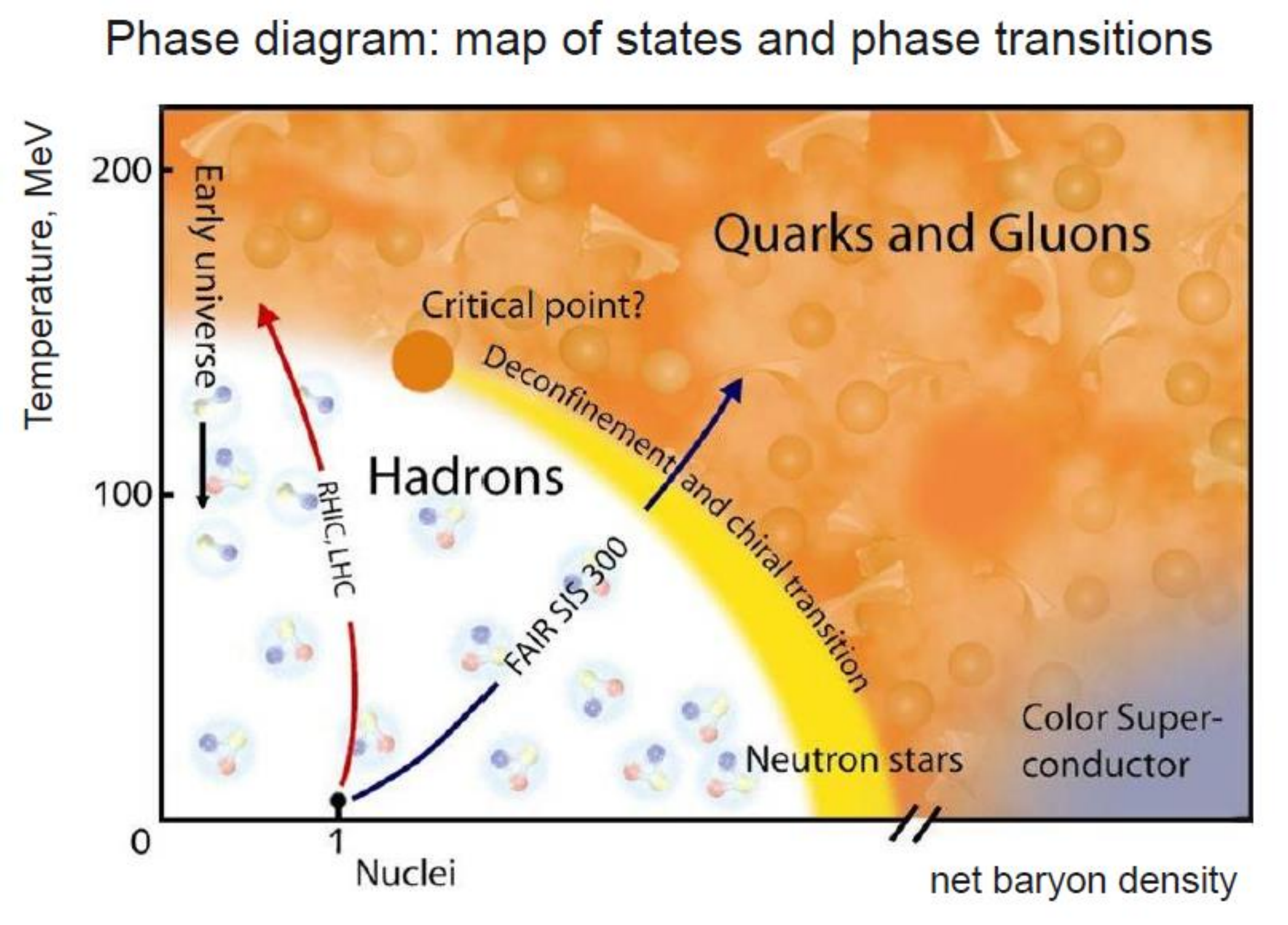


Quark-Gluon Plasma

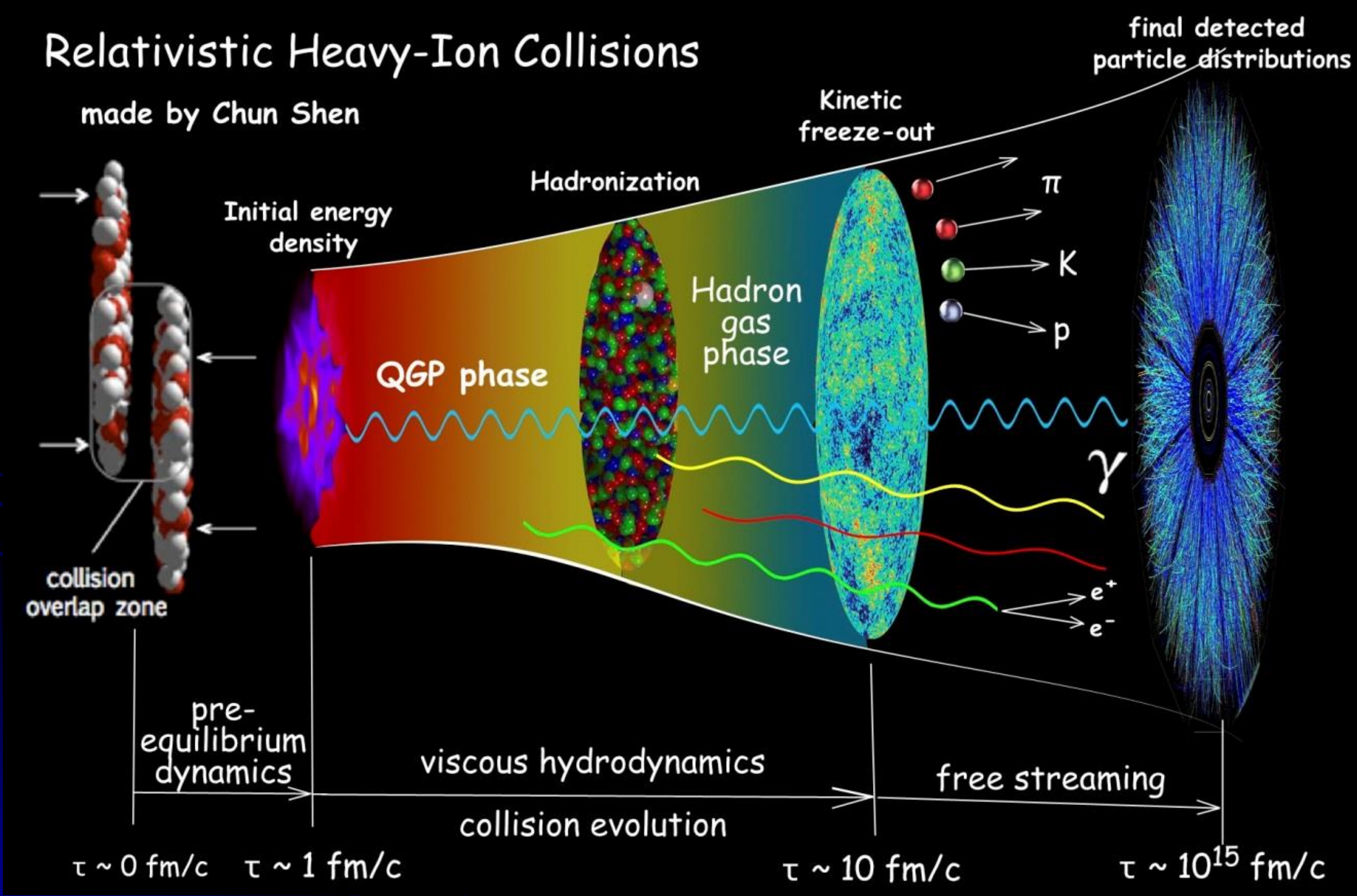
- A state of matter where quarks and gluons move freely over distances large in comparison to the typical size of a hadron
- Paradigm shift with results from RHIC
  - Expected: weakly interacting gas
  - Observed: strongly coupled liquid



QCD phase diagram



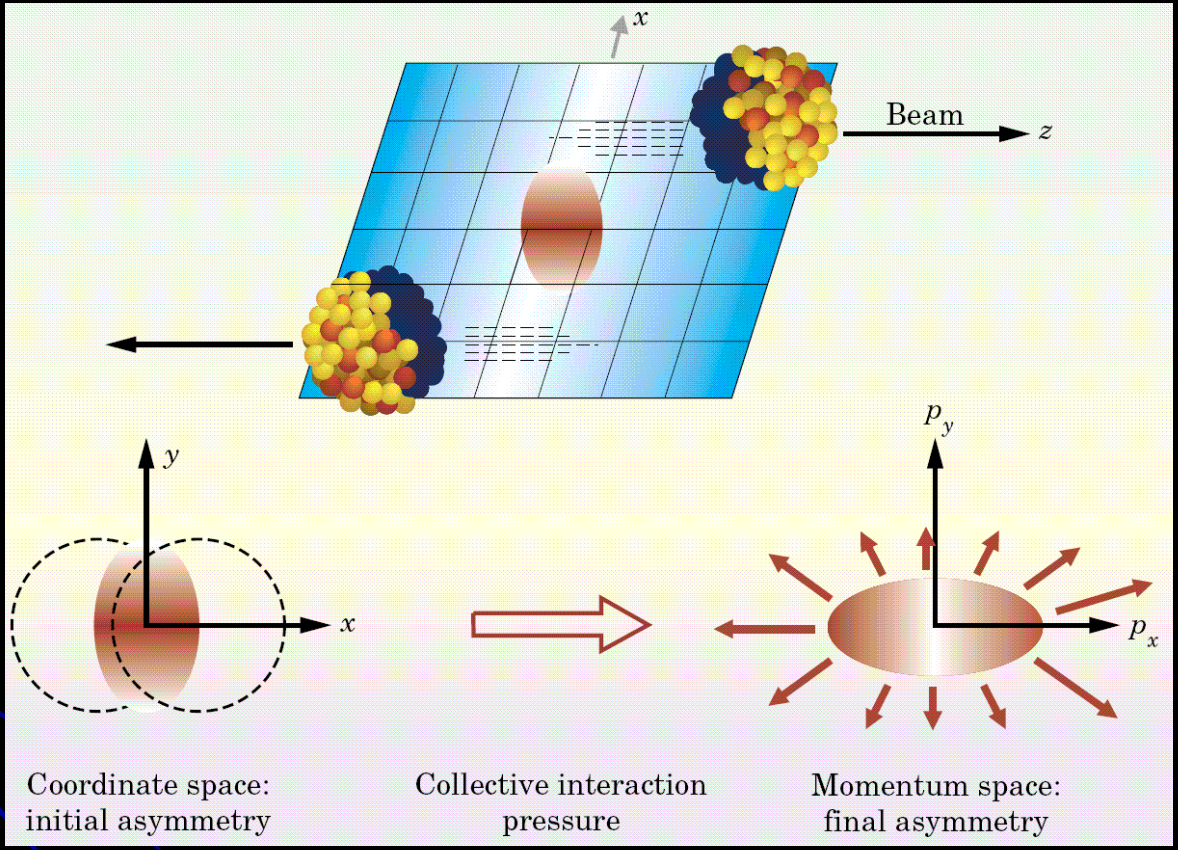
Stages



Relativistic Heavy-Ion Collisions
made by Chun Shen
collision overlap zone
Initial energy density
QGP phase
Hadronization
Hadron gas phase
Kinetic freeze-out
final detected particle distributions
π
K
p
γ
e+
e-
pre-equilibrium dynamics
viscous hydrodynamics
free streaming
collision evolution
τ ~ 0 fm/c
τ ~ 1 fm/c
τ ~ 10 fm/c
τ ~ 10^15 fm/c

Anisotropic flow

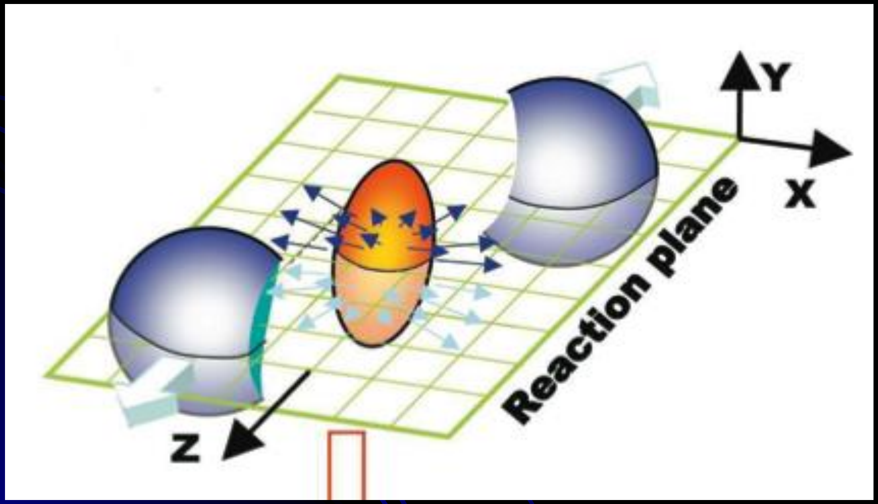
Anisotropic flow

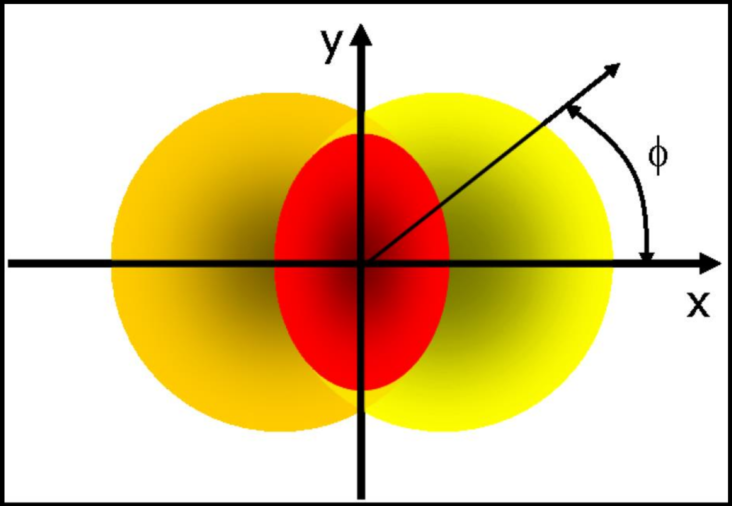


- The transfer of initial anisotropy in coordinate space into the final anisotropy in momentum space via interactions between the constituents is the anisotropic flow phenomenon

Initial anisotropy

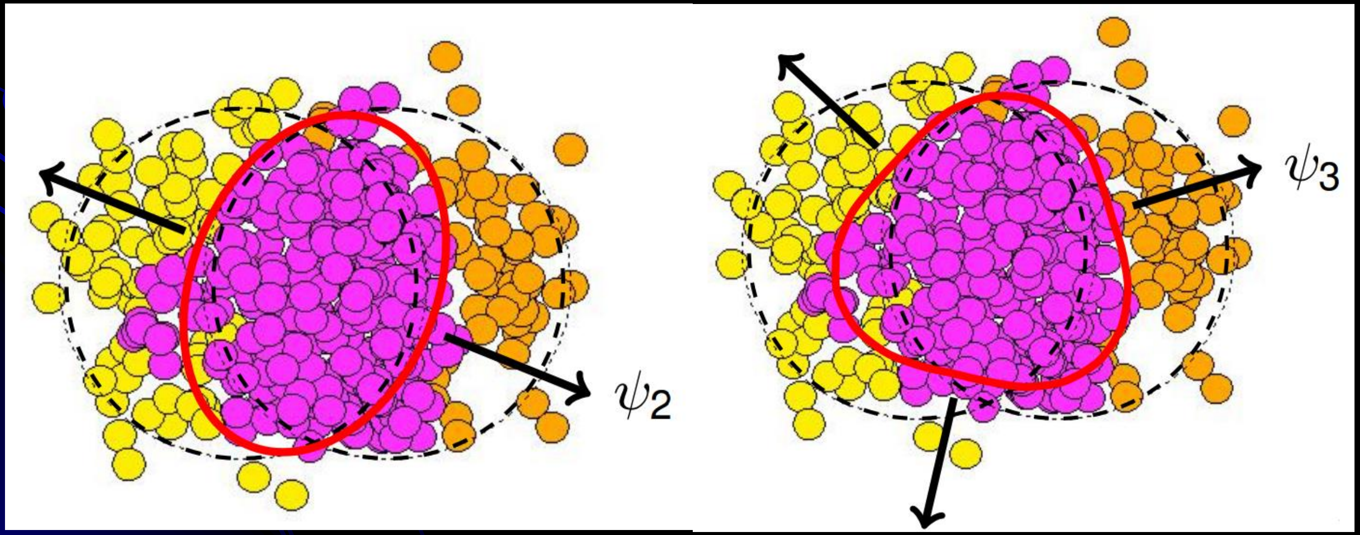
- **Non-central heavy-ion collision** is a prime example
  - Due to geometry of collision the resulting volume containing interacting matter is anisotropic in coordinate space
  - To leading order this anisotropic volume is ellipsoidal
- **Geometry-dominated regime**





Initial anisotropy

- In the **most-central heavy-ion collisions** more subtle cases of initial anisotropic volume can occur due to fluctuations of participating nucleons
  - These fluctuations can (in principle) generate any type of anisotropic volume in coordinate space
- **Fluctuation-dominated regime**

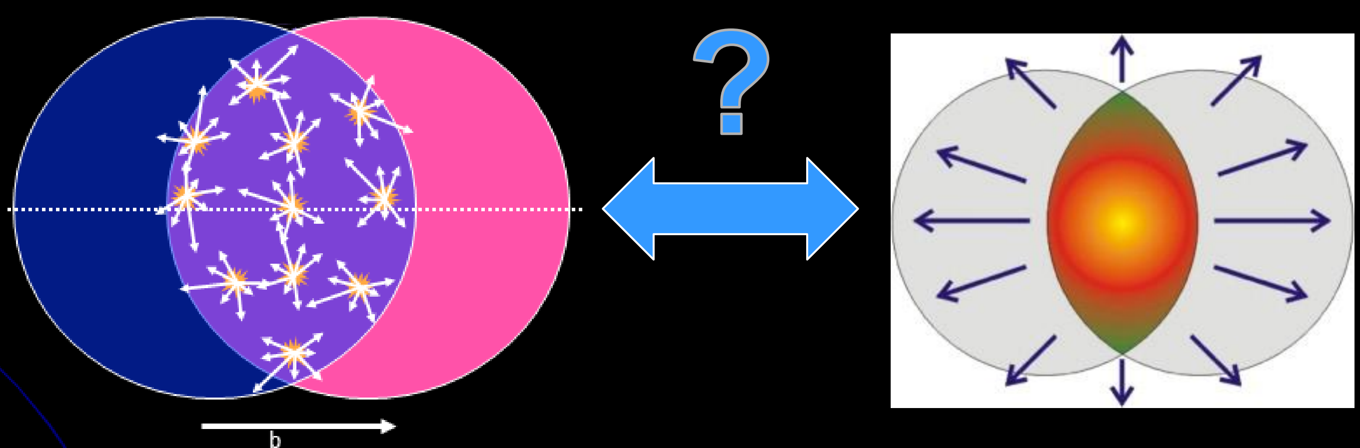


Transfer of anisotropy

- **Thermalisation** ⇔ large number of mutual interactions among constituents
- Large number of mutual interactions ⇔ large number of interacting particles confined to a small volume
- Large number of interacting particles confined to a small volume ⇔ **heavy-ion collisions**
  - It is much less probable that thermalisation will be reached in collisions of lighter objects (e.g. in p+p collisions)
  - Once we have a thermalized medium we can start naturally to speak about thermodynamic concepts like temperature, pressure, equation of state, etc.

Transfer of anisotropy

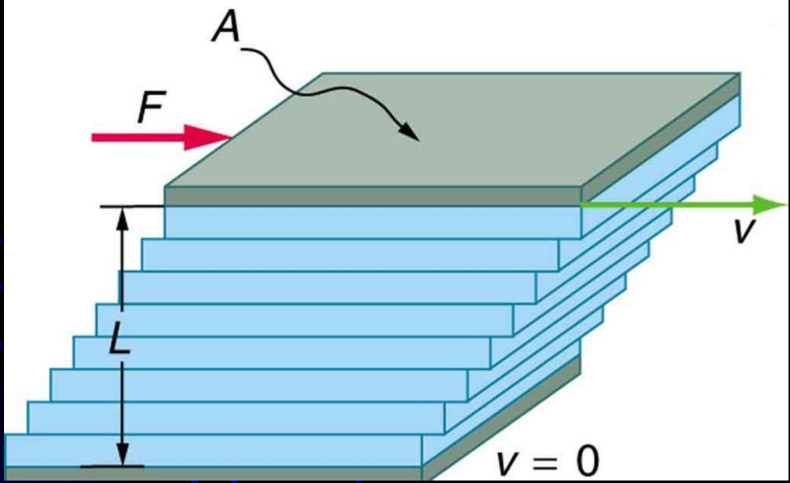
- Two conceptually different notions of anisotropy:
  - **Coordinate space anisotropy:** Is the volume containing the interacting particles which are produced in heavy-ion collision anisotropic or not?
  - **Momentum space anisotropy:** Is the final-state azimuthal distribution of resulting particles which are recorded in the detector anisotropic or not?
- **A priori**, these two anisotropies are **unrelated**

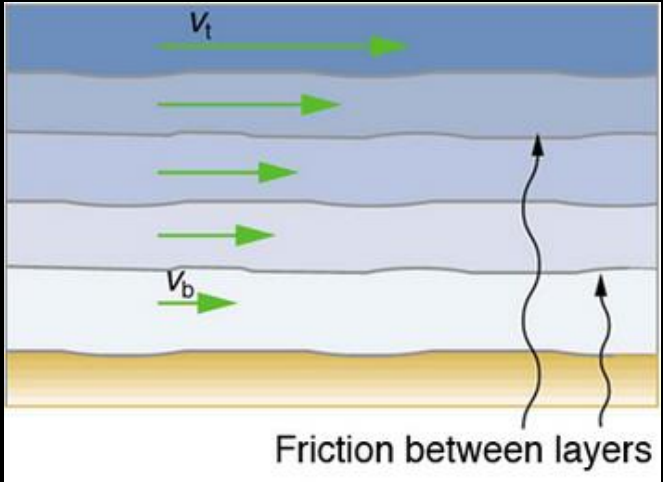


made by Mike Lisa

System properties

- By measuring event-by-event anisotropies in the resulting momentum distribution of detected particles, we can probe the properties of produced matter
- Example: **Shear viscosity**

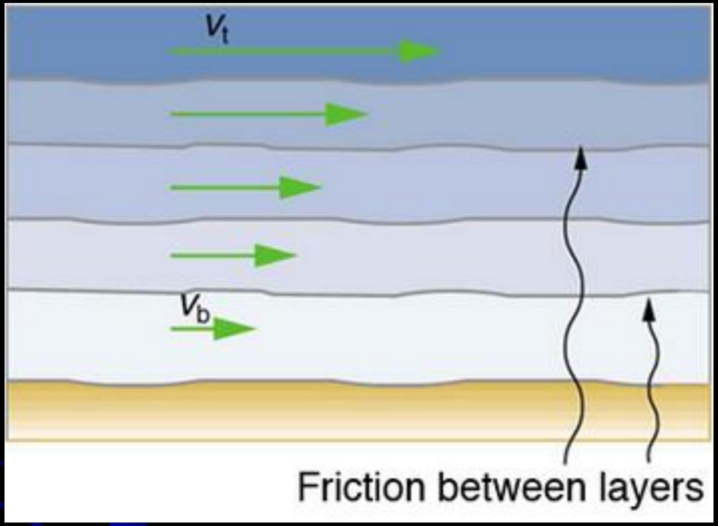


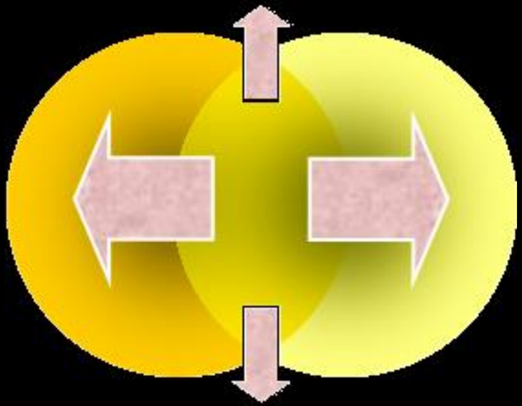


- Shear viscosity characterizes quantitatively the resistance of the liquid or gas to the parallel displacement of its neighbouring layers

Shear viscosity

- Shear viscosity ‘fights’ against anisotropic flow

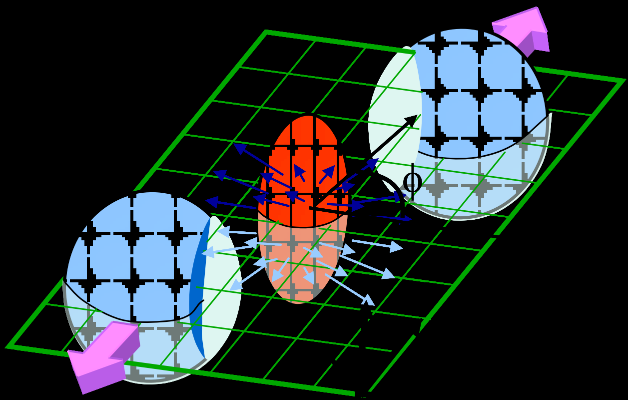


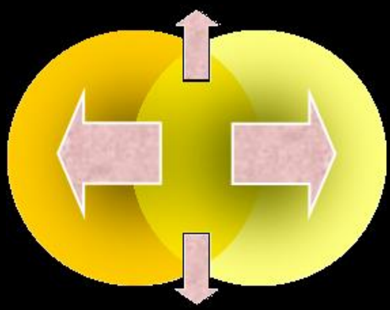


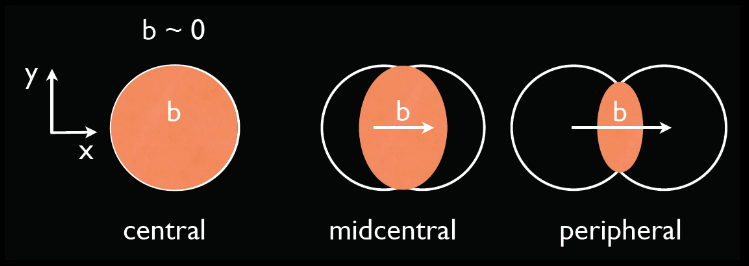
- Perfect liquid ⇔ kinematic shear viscosity negligible ⇔ anisotropic flow develops easily
- The ratio of shear viscosity to entropy density (η/s) has a lower bound: **$1/4\pi$** (obtained in strong-coupling calculations based on the AdS/CFT conjecture)

P. Kovtun, D. T. Son, and A. O. Starinets, Phys. Rev. Lett. 94 (2005) 111601, arXiv:hep-th/0405231

How to quantify flow?







- S. Voloshin and Y. Zhang, Z.Phys.C70:665-672,1996: **Fourier series**

$$E\frac{d^3N}{d^3\vec{p}} = \frac{1}{2\pi}\frac{d^2N}{p_T\,dp_T\,dy}\left(1+\sum_{n=1}^{\infty}2v_n\cos\left(n\left(\phi-\Psi_{\mathrm{RP}}\right)\right)\right)$$

$$v_n = \langle\cos(n(\phi-\Psi_{\mathrm{RP}}))\rangle$$

- Harmonics v_n quantify anisotropic flow
  - v_1 is directed flow, v_2 is elliptic flow, v_3 is triangular flow, etc.

Historical account

- In-plane elliptic flow was first suggested as a signature of collective flow in relativistic nuclear collisions by Jean-Yves Ollitrault:

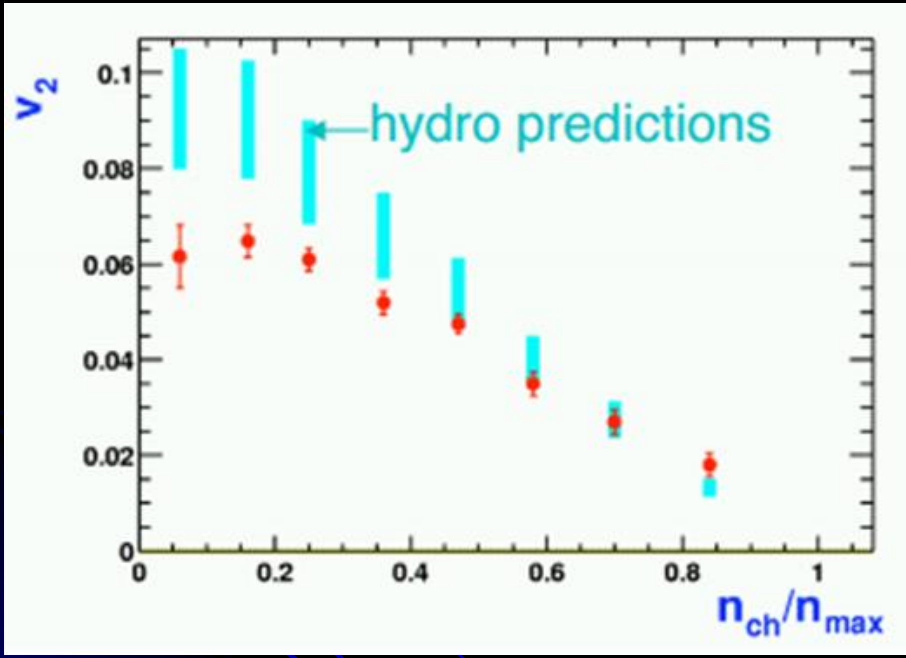
Anisotropy as a signature of transverse collective flow
Phys. Rev. D **46**, 229 – Published 1 July 1992
Jean-Yves Ollitrault

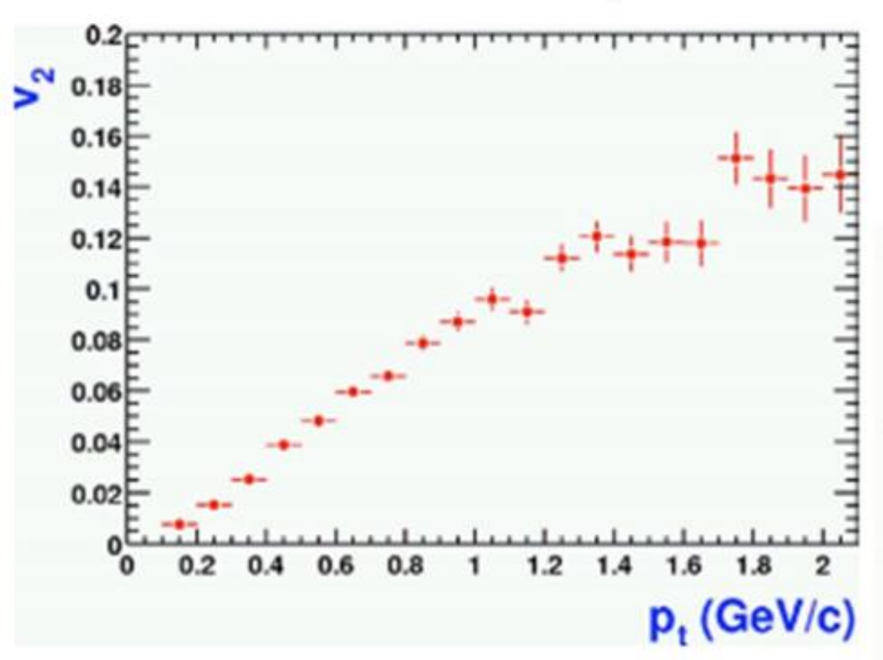
  - Monumental paper, **900+ citations**
- In-plane elliptic flow was first experimentally measured in Au-Au collisions at Brookhaven Alternate Gradient Synchrotron (AGS) [E877 Collaboration]

Energy and charged particle flow in $10.8A$ GeV/c Au+Au collisions
J. Barrette *et al.* (E877 Collaboration)
Phys. Rev. C **55**, 1420 – Published 1 March 1997; Erratum Phys. Rev. C **56**, 2336 (1997)

Discovery of v_2 at RHIC

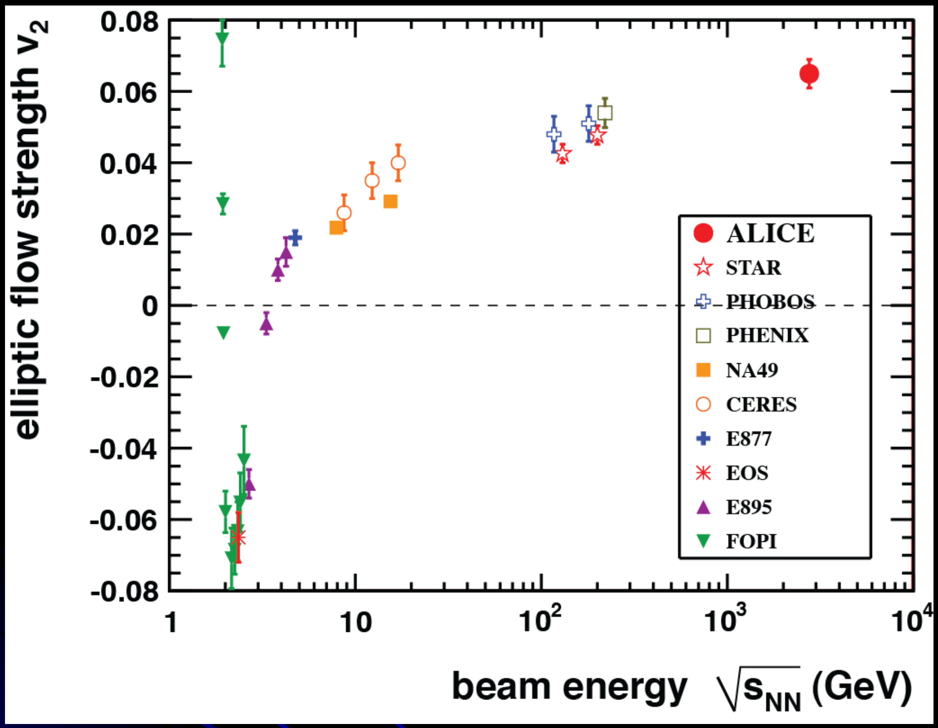
- STAR, Phys. Rev. Lett. **86**, 402 (2001)





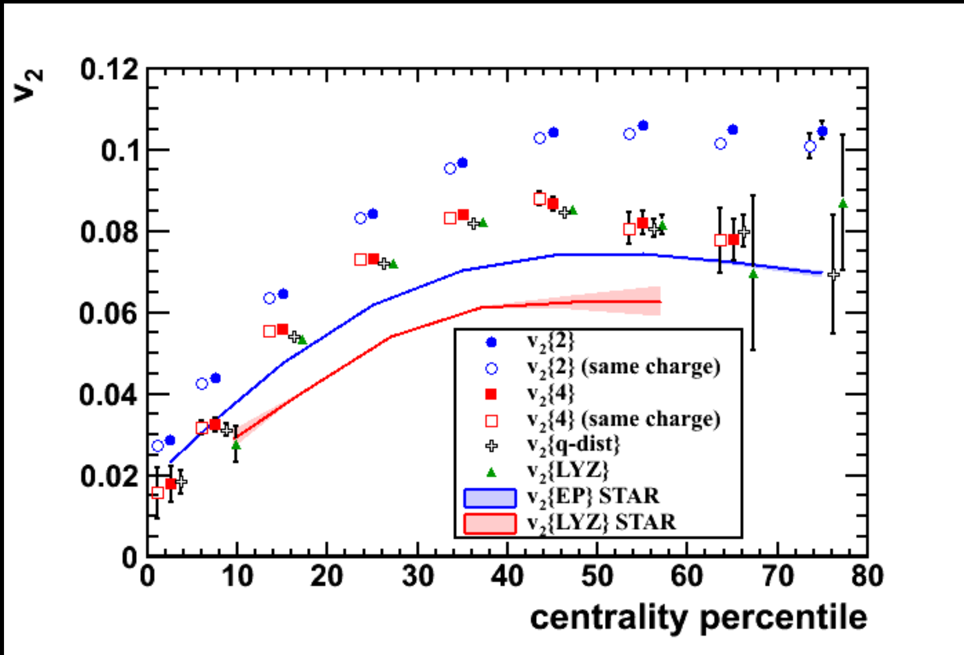
- For the first time hydro predictions and data agreed in Au-Au collisions at 130 GeV (LHS, central collisions)

Discovery of v_2 at LHC



ALICE, Phys. Rev. Lett. 105, 252302 (2010)

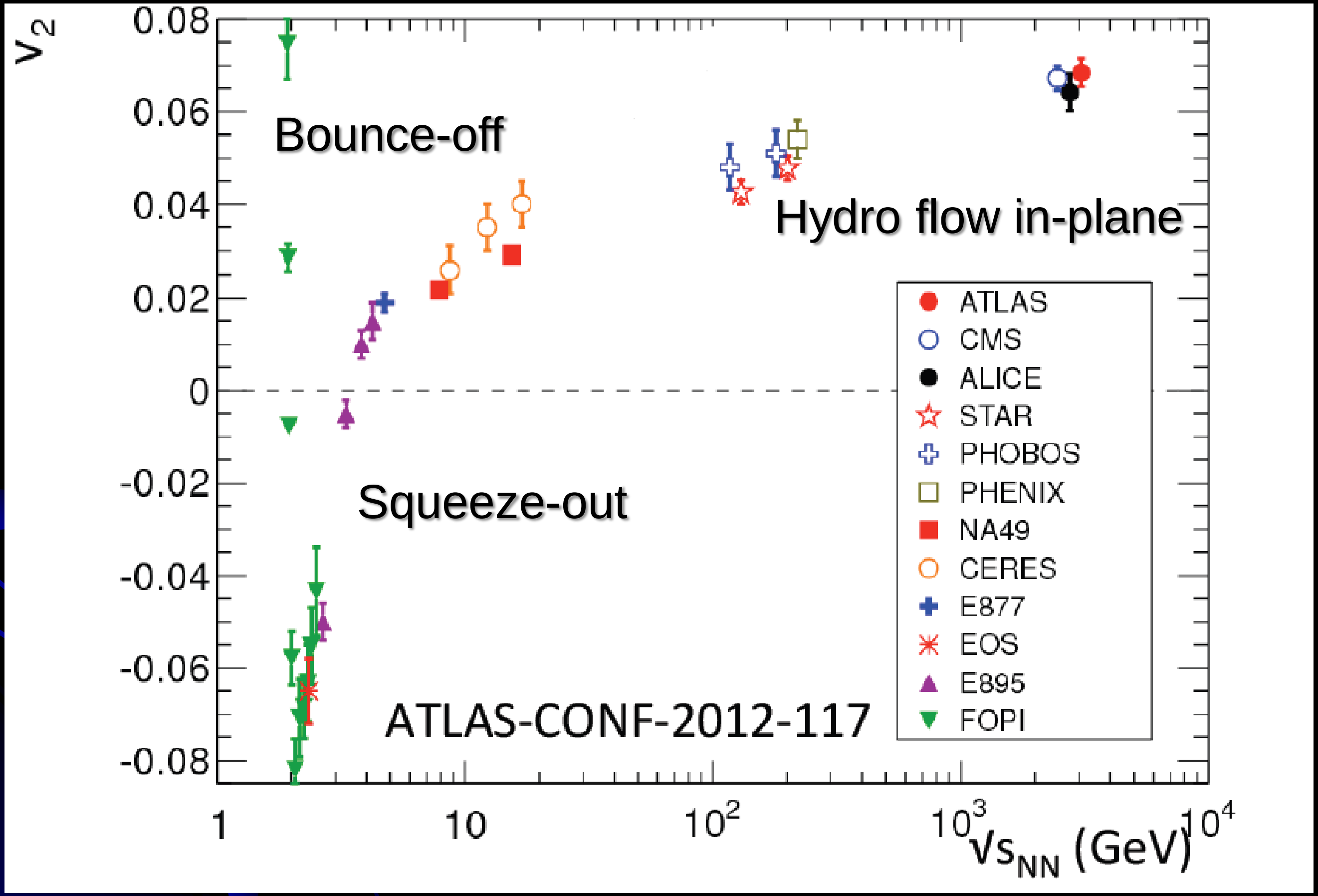
Cited by now > 500 times!



Elliptic flow increases by ~ 30% at 2.76 TeV when compared to RHIC energies

Historical snapshot

- Non-trivial dependence on collision energy

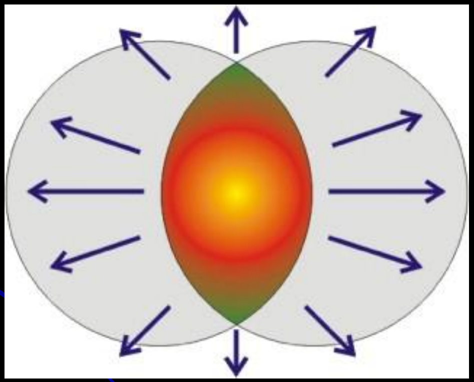


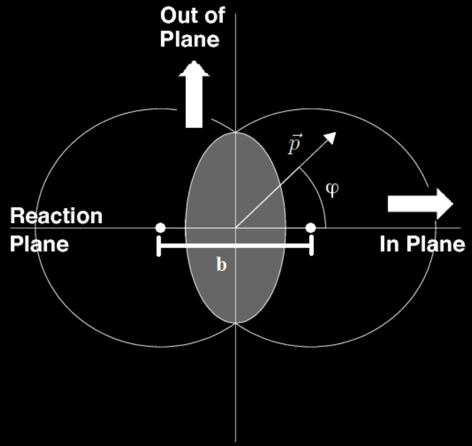
Analysis technique and flow observables

The 'flow principle'

- Can we estimate the amplitudes v_n without the explicit knowledge of symmetry planes?

$$v_n = \langle \cos(n(\phi - \Psi_{RP})) \rangle$$

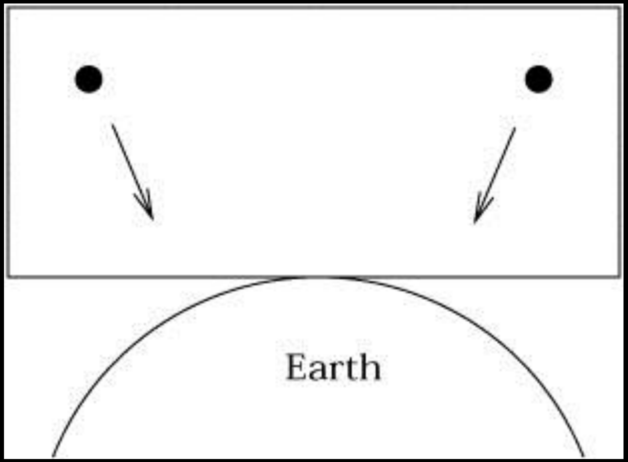




- **The 'flow principle':** Correlations among produced particles are induced solely by correlation of each particle to the reaction plane

Analogy with gravity

- Falling bodies appear to be correlated in gravitational field due to correlation of each body with the common center of gravity



- Geometry of massive body => gravitational field
- Geometry of heavy-ion collision => the pressure gradients
  - Particle trajectories are the same whether they would be emitted simultaneously or one-by-one: **statistical independence**

Correlation techniques

- As an outcome of 'flow principle' we have **factorization**

event average → ; particle average →

$$\left\langle\!\left\langle e^{in(\phi_1-\phi_2)} \right\rangle\!\right\rangle = \left\langle\!\left\langle e^{in(\phi_1-\Psi_{RP}-(\phi_2-\Psi_{RP}))} \right\rangle\!\right\rangle = \left\langle\!\left\langle \left\langle e^{in(\phi_1-\Psi_{RP})} \right\rangle \left\langle e^{-in(\phi_2-\Psi_{RP})} \right\rangle \right\rangle\!\right\rangle = \langle v_n^2 \rangle$$

- Estimating **higher order moments** v_n^k
- Behind the scene: Factorization of joint multivariate p.d.f.

$$f(\varphi_1, \ldots, \varphi_n) = f_{\varphi_1}(\varphi_1) \cdots f_{\varphi_n}(\varphi_n)$$

- If the measured azimuthal correlators have contribution only from flow correlations, factorization works exactly to all orders

Correlation techniques

- We have to correlate different particles, self-correlations are useless (yet dominant!) contribution in averages

$$\langle 2\rangle \equiv \langle \cos n(\phi_1-\phi_2)\rangle\ , \qquad \phi_1 \neq \phi_2$$

$$\langle 4\rangle \equiv \langle \cos n(\phi_1+\phi_2-\phi_3-\phi_4)\rangle\ , \qquad \phi_1 \neq \phi_2 \neq \phi_3 \neq \phi_4$$

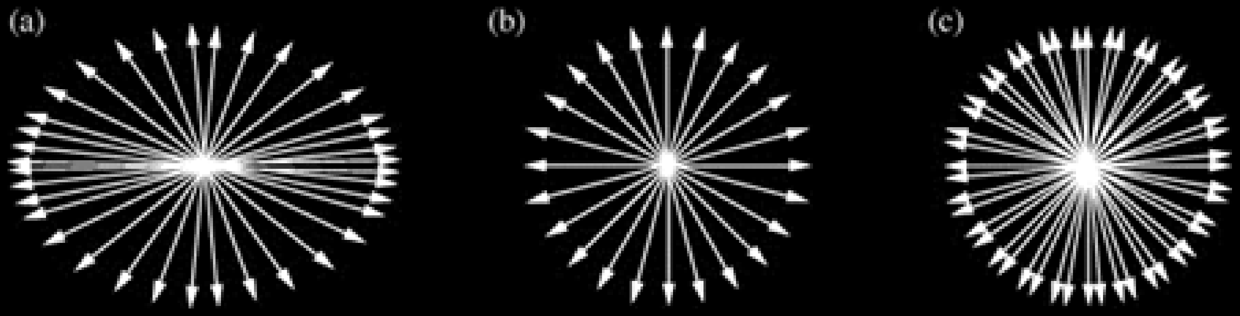
- Only isotropic correlators are non-trivial
- Analytic result:

$$\langle\cos(n_1\varphi_1+\cdots+n_k\varphi_k)\rangle = v_{n_1}\cdots v_{n_k}\cos(n_1\Psi_{n_1}+\cdots+n_k\Psi_{n_k})$$

R. S. Bhalerao, M. Luzum and J.-Y. Ollitrault,’ PRC **84** 034910 (2011)

Nonflow

- 'Direct correlations', a.k.a. **nonflow**



Flow | No flow | Nonflow

- Nonflow: Typically all sources of correlations in momentum space among produced particles which 'have nothing to do' with the reaction plane orientation
  - Generally involve only a small subset of the produced particles
  - Factorization of underlying multivariate p.d.f. is broken

$$f(\varphi_1, \ldots, \varphi_n) \neq f_{\varphi_1}(\varphi_1) \cdots f_{\varphi_n}(\varphi_n)$$

Cumulants

- Concrete example: What are **$v_n\{2\}$** and **$v_n\{4\}$**?

$$\sqrt{c_n\{2\}} = \sqrt{\langle\langle 2\rangle\rangle} = v_n\,,$$
$$\sqrt[4]{-c_n\{4\}} = \sqrt[4]{-\langle\langle 4\rangle\rangle + 2\cdot\langle\langle 2\rangle\rangle^2} = \sqrt[4]{-v_n^4 + 2v_n^4} = v_n$$

- In an actual experiment due to nonflow and event-by-event flow fluctuations the above lines are not exact, therefore estimates of v_n from 2- and 4-particle cumulants will be **systematically different**
  - This systematic difference is indicated with separate notations:

$$v_n\{2\} \equiv \sqrt{c_n\{2\}}\,,$$
$$v_n\{4\} \equiv \sqrt[4]{-c_n\{4\}}$$

Precision era at Run 2

- When only flow correlations are present, and if flow harmonic v was estimated with k-particle correlator, for the data set having N events, each of which has M particles, to leading order:

$$\sigma_v \sim \frac{1}{\sqrt{N}} \frac{1}{M^{k/2}} \frac{1}{v^{k-1}}$$

- In the heavy-ion collisions with a large elliptic flow and large multiplicity, this scaling is a ‘great news’

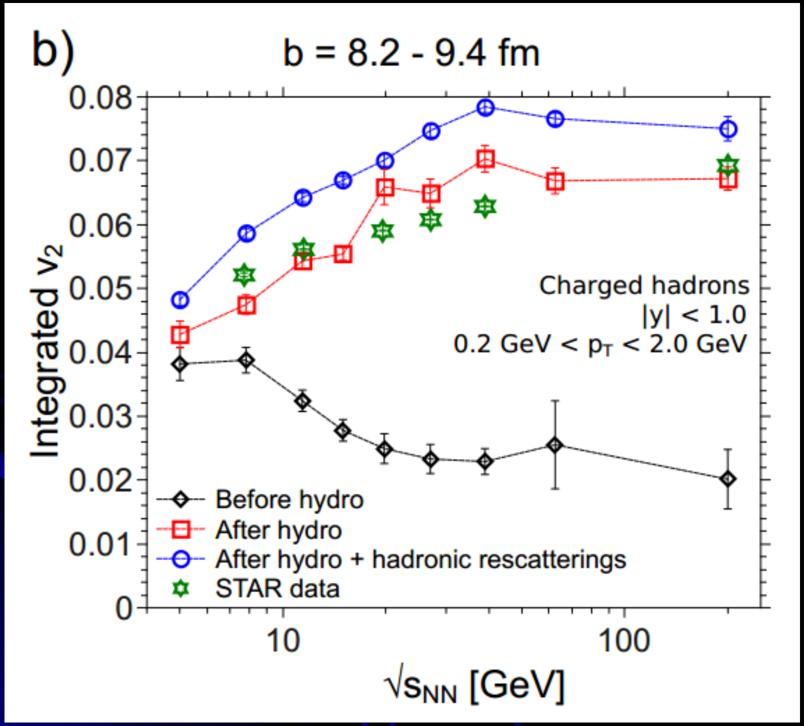
Theoretical predictions for Run 2

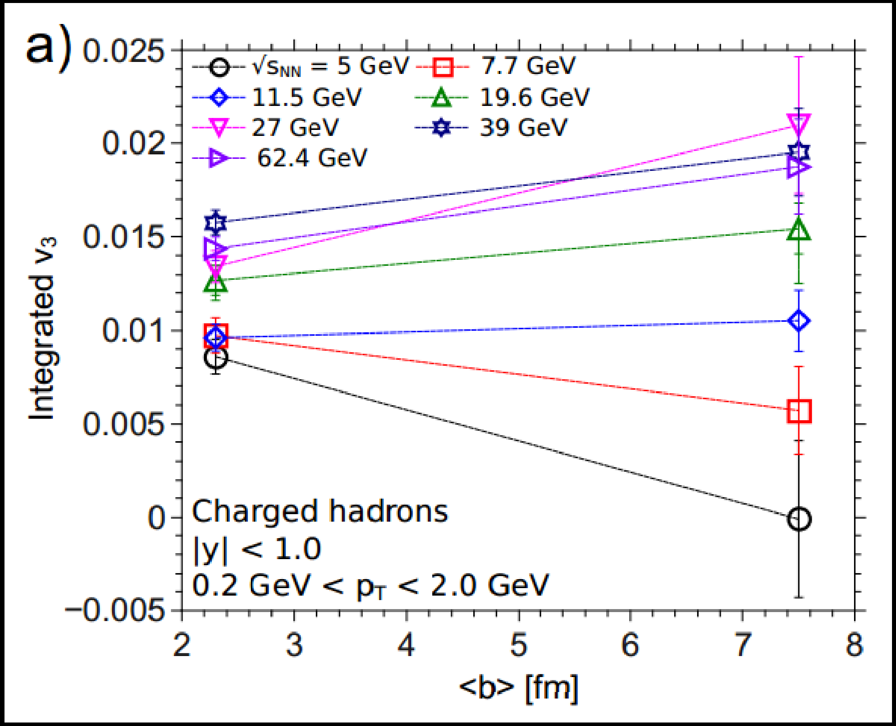
Executive summary

- Theoretical expectations for the transition from 2.76 TeV to 5.02 TeV:
  - Increase/decrease of initial spatial eccentricities?
  - Flow saturation?
  - Hydrodynamic flow out-of-plane?
  - Pinning down temperature dependence of η/s?
  - Elliptic flow increases for light and decreases for heavy particles at low p_T?
  - Different change in relative contributions of various stages of system evolution for different harmonics?

Energy dependence

- J. Auvinen and H. Petersen, J. Phys. Conf. Ser. 503 (2014) 012025, arXiv:1310.7751

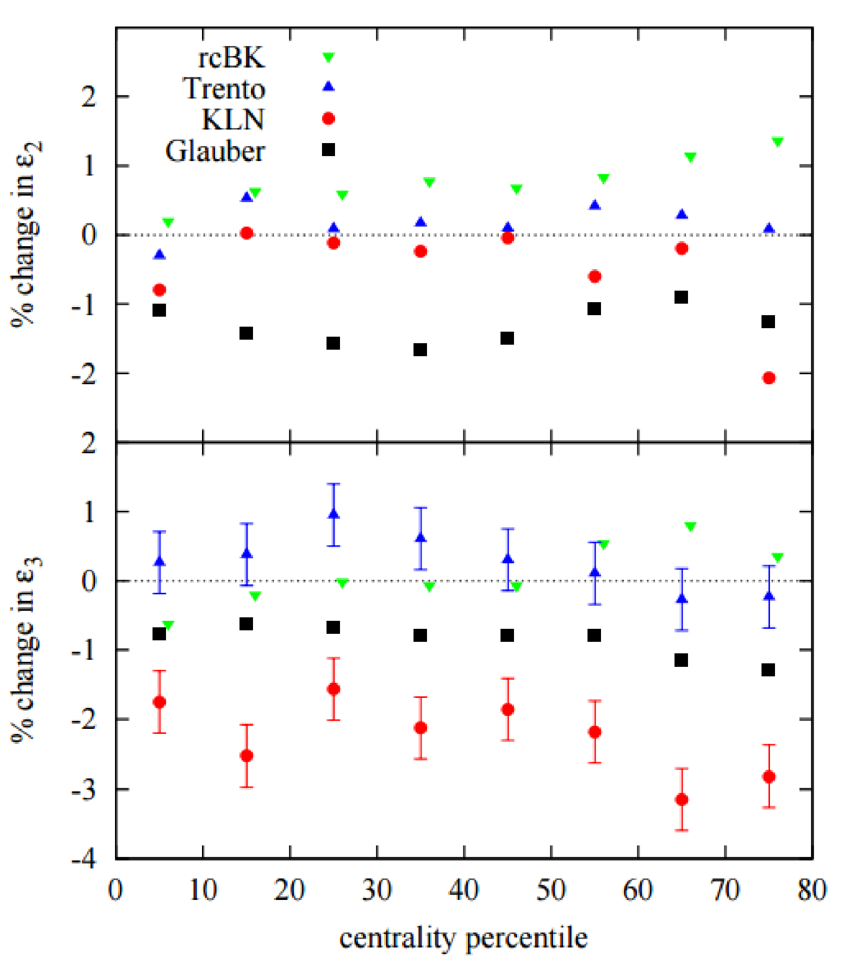




The relative importance of various stages in the system evolution as a function of collision energy can vary for each flow coefficient

Energy dependence

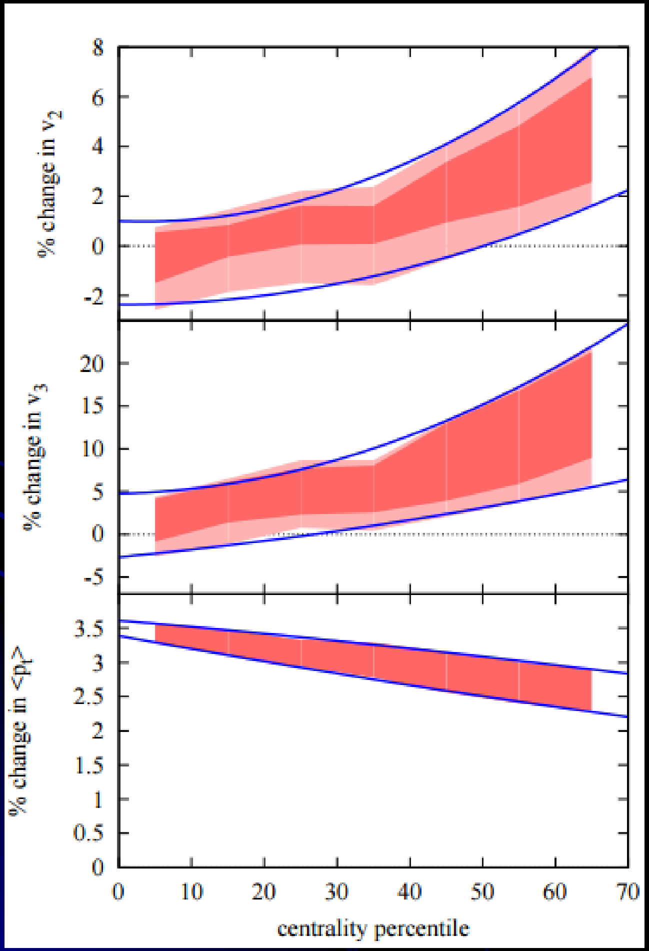
- J. Noronha-Hostler, M. Luzum, and J.-Y. Ollitrault, arXiv:1511.06289



- Initial state models: MC-Glauber, MC-KLN, MCrcBK and Trento
- Each of these models uses the measured nucleon-nucleon inelastic cross-section as input: 64 mb at Run 1 and 70 mb at Run 2 (extrapolation)
- Predict both increase and decrease of eccentricities

Energy dependence

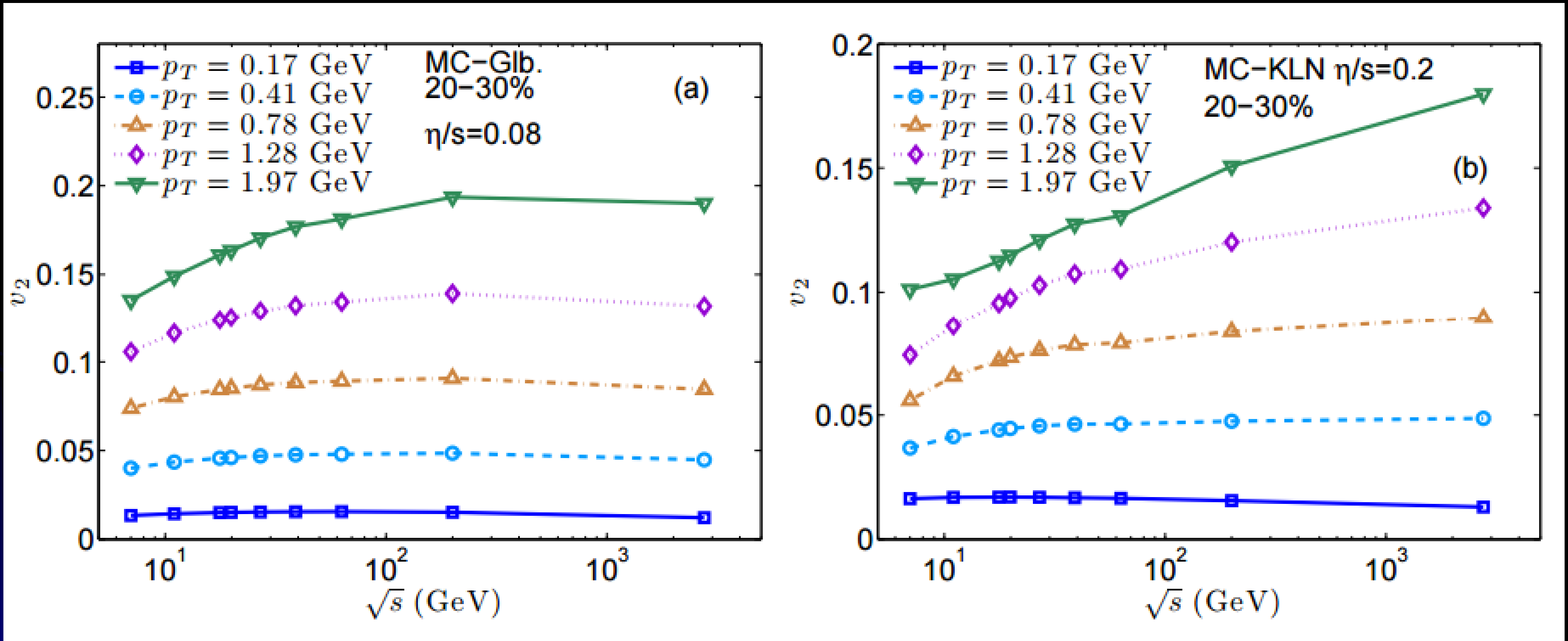
- J. Noronha-Hostler, M. Luzum, and J.-Y. Ollitrault, arXiv:1511.06289



- Compared to the Run 1 LHC measurements, it is predicted that the mean transverse momentum will increase between 2.5%-3.5%
- v_2 and v_3 will see the largest increases in peripheral collisions, while in central collisions they will see little change
- Flow saturation in central collisions

Flow saturation

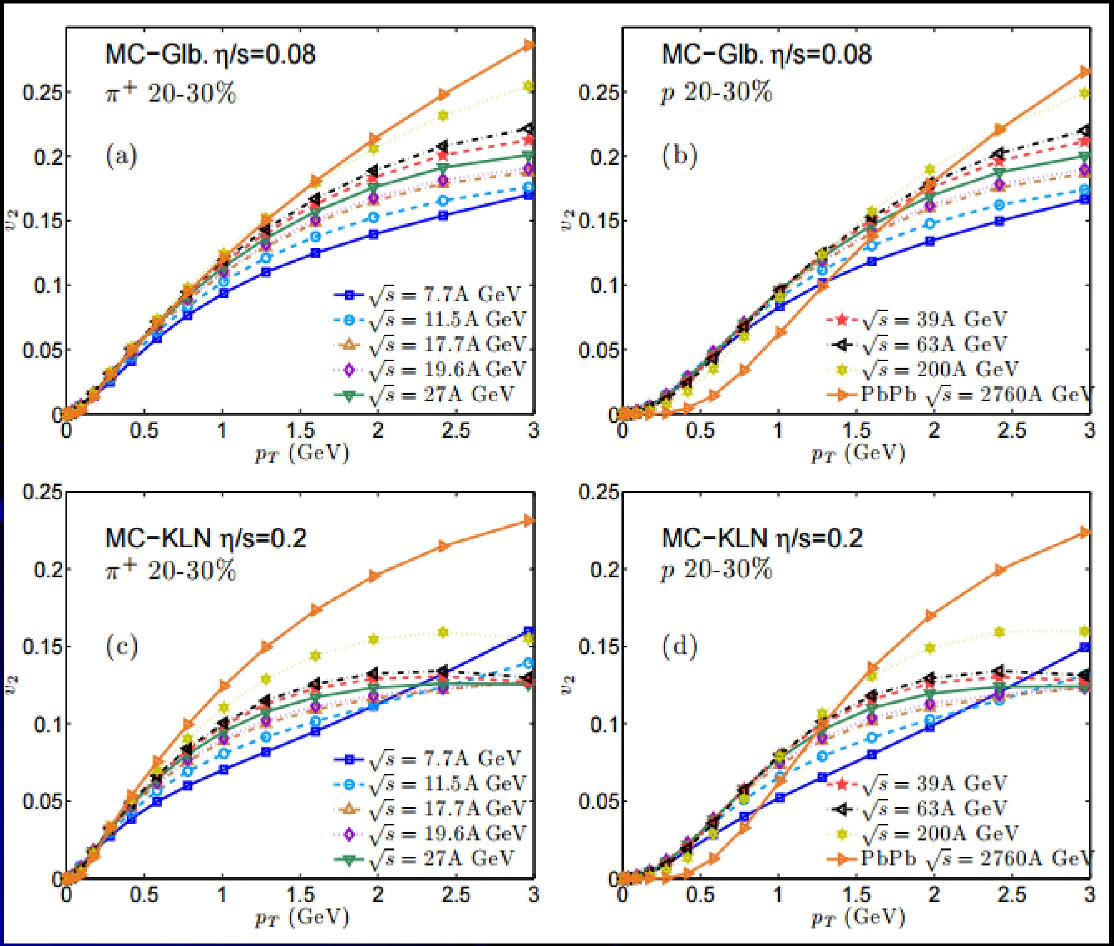
- C. Shen and U. Heinz, Phys. Rev. C85 (2012) 054902, arXiv:1202.6620



In viscous hydro the "saturation" of elliptic flow is shifted to higher collision energies by shear viscous effects

Flow saturation

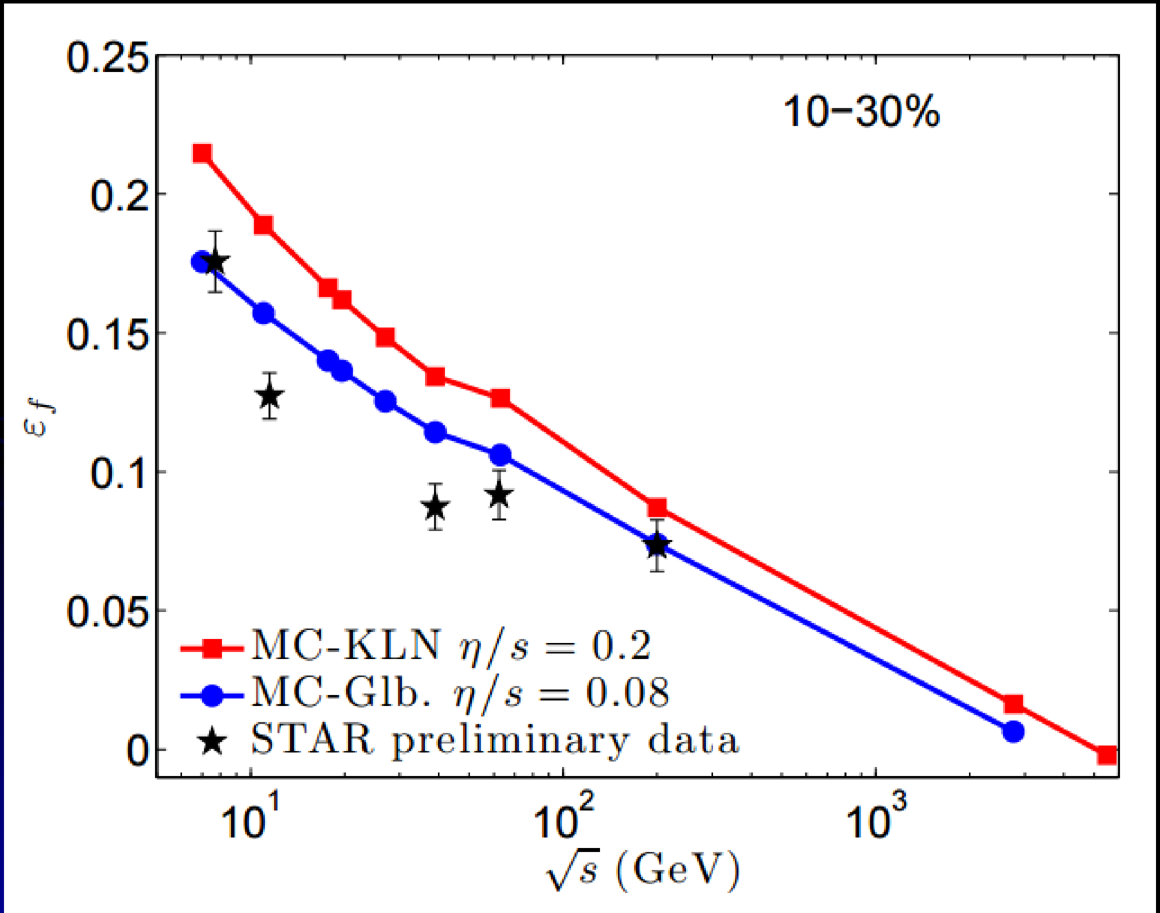
- C. Shen and U. Heinz, Phys. Rev. C85 (2012) 054902, arXiv:1202.6620



Interplay between radial and elliptic flow leads to a subtle cancellation between increasing contributions from light and decreasing contributions from heavy particles!

Hydro flow out-of-plane!?

- C. Shen and U. Heinz, Phys. Rev. C85 (2012) 054902, arXiv:1202.6620

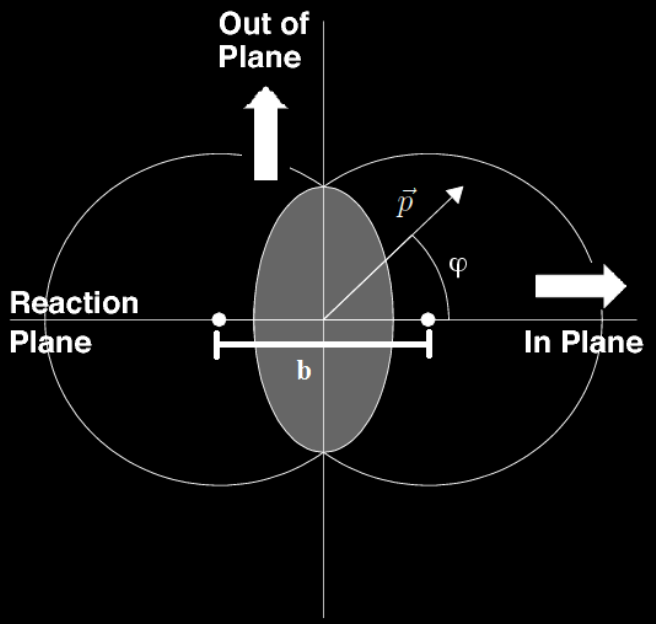


At higher collision energy the system lives longer and has actually enough time to become elongated along the reaction plane, instead of its original elongation perpendicular to it.

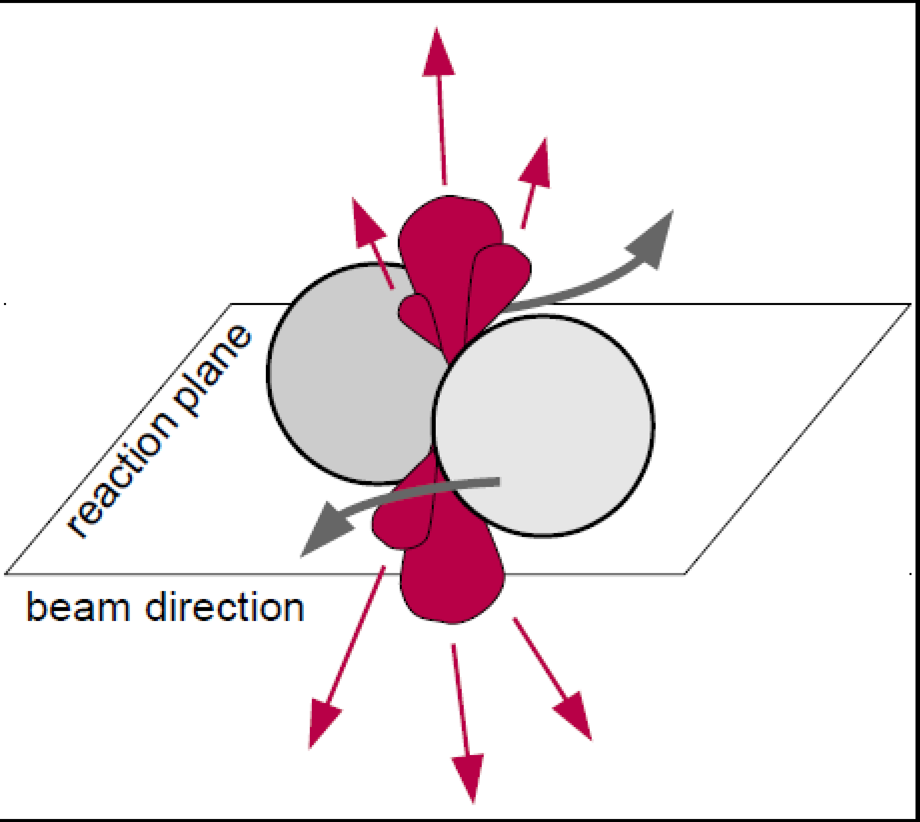
Such contribution comes with the negative signature, the overall flow might decrease at Run 2!

Negative v_2

- 'Squeeze-out' a.k.a. elliptic flow 'out-of-plane'
  - Can be both trivial (shadowing) and non-trivial (hydro)

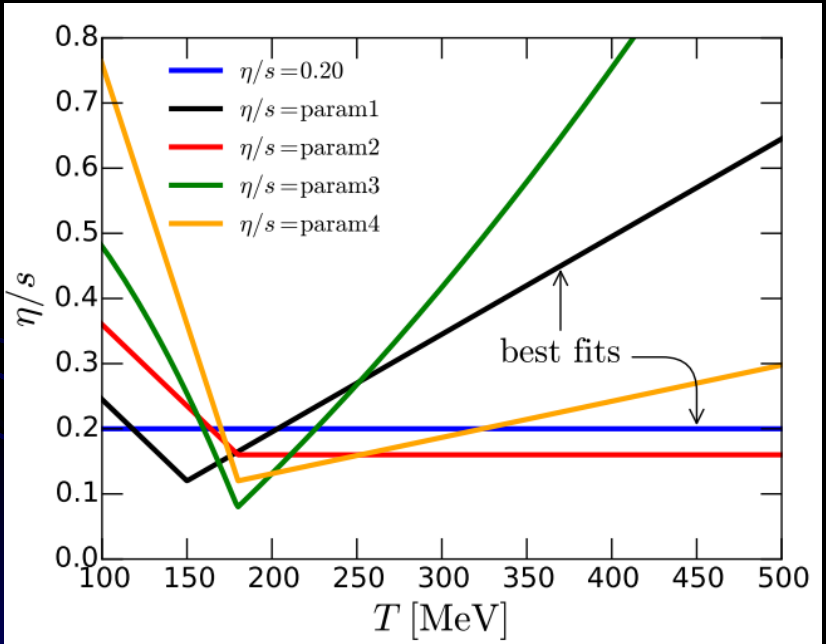


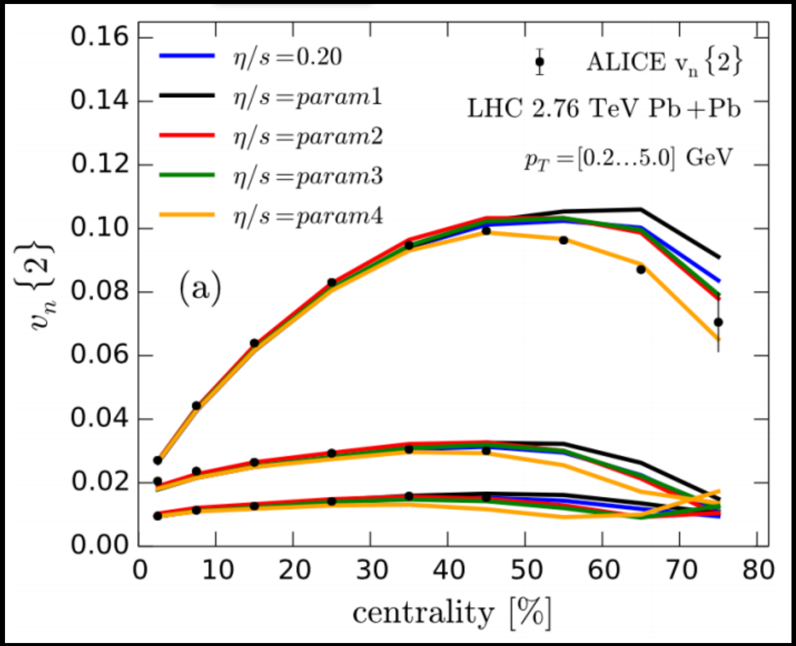
$$\sqrt{s_{NN}} \sim 2-4\,GeV$$



η/s(T)

- Study of temperature dependence of transport coefficients has just begun
- H. Niemi, K. J. Eskola, R. Paatelainen, Phys. Rev. C 93, 024907 (2016)

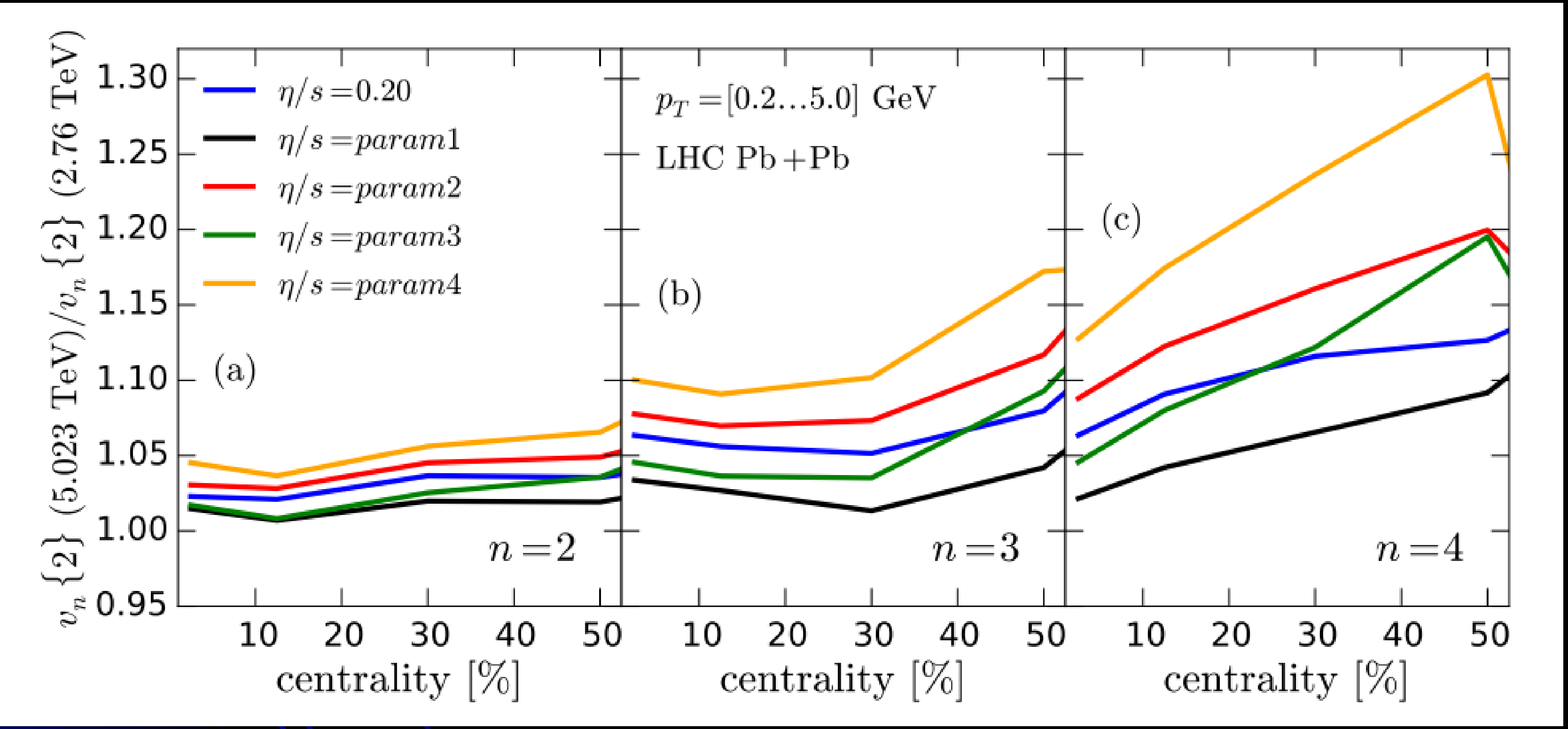




This state-of-the-art model quantitatively describes the Run 1 data

η/s(T)

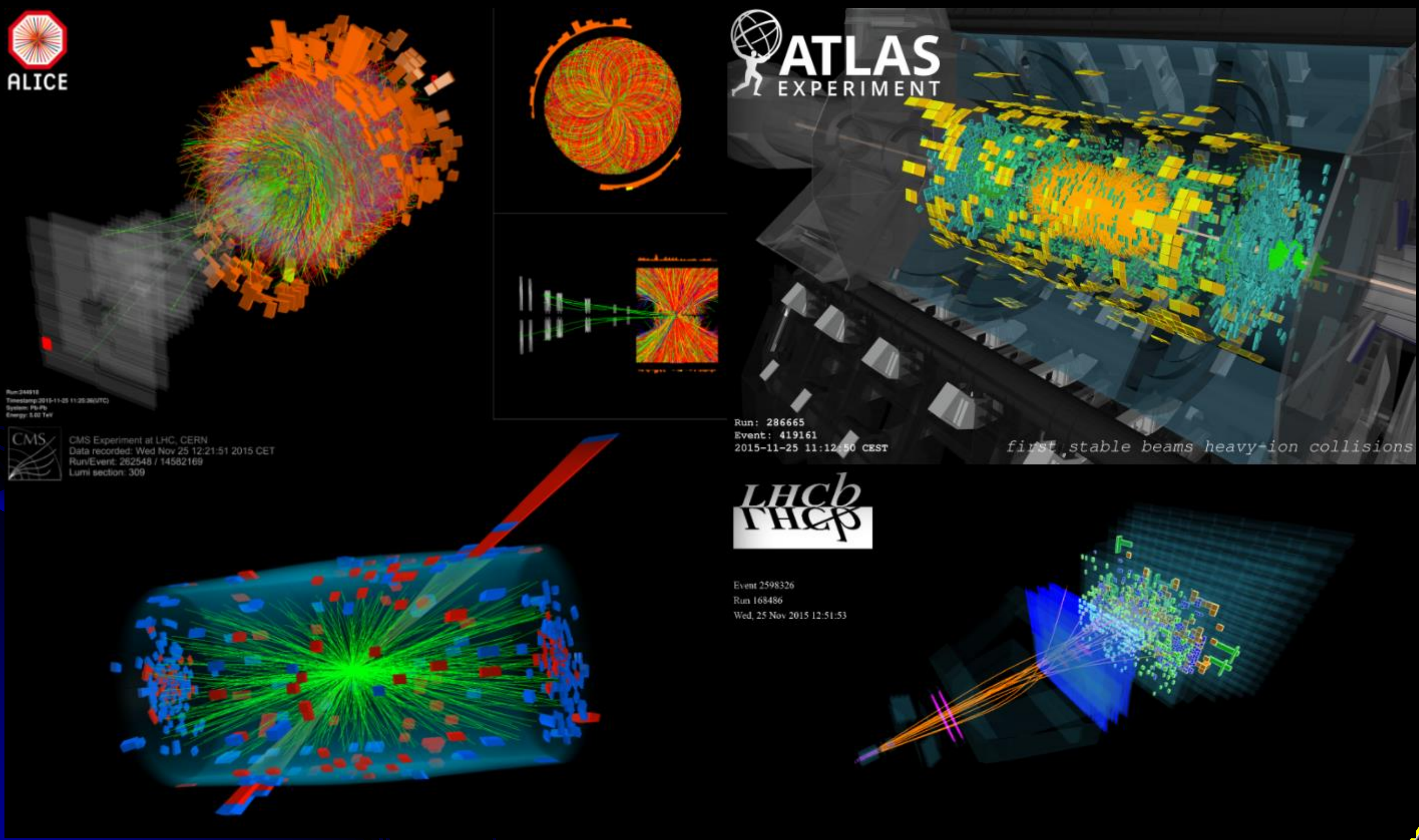
- H. Niemi, K. J. Eskola, R. Paatelainen, and K. Tuominen, Phys. Rev. C 93, 014912 (2016) arXiv:1511.04296 [hep-ph]



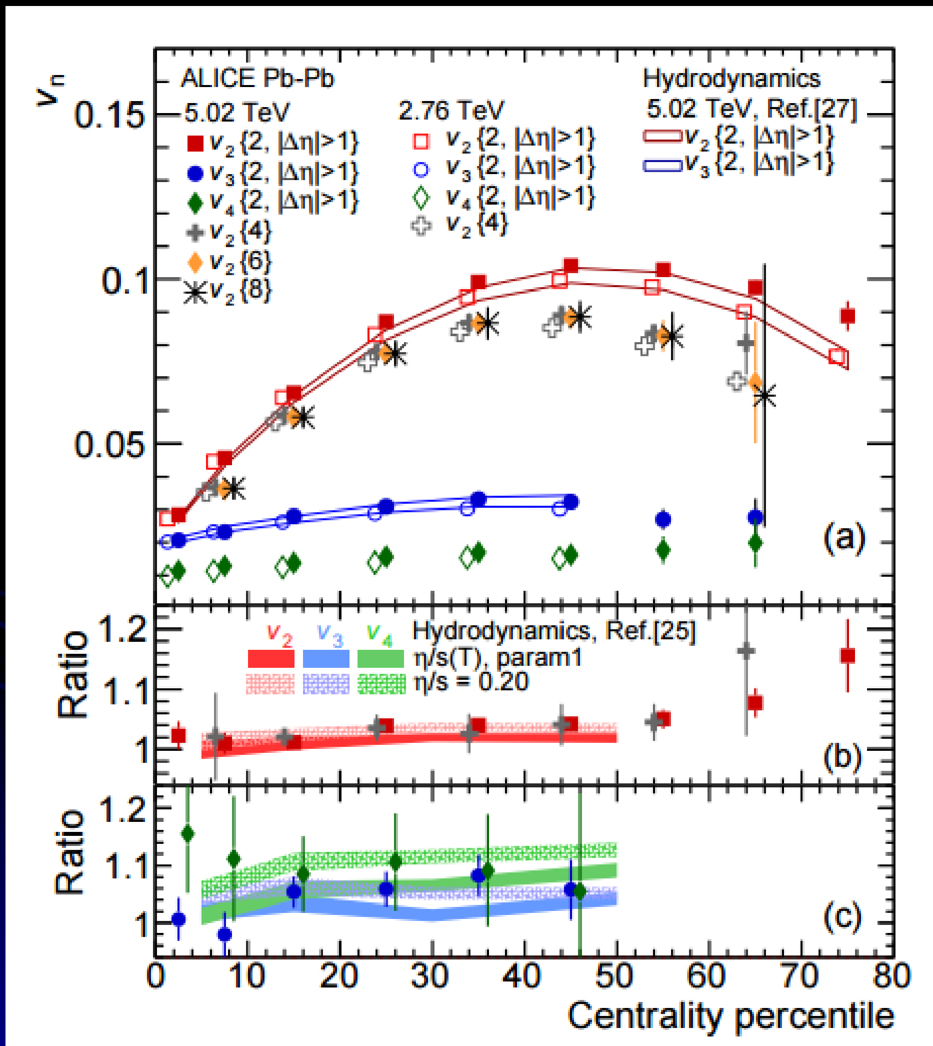
Compared to the Run 1 LHC measurements, higher harmonics will show bigger and non-trivial increase as a function of centrality

First results from Run 2

Run 2 collisions



Centrality dependence

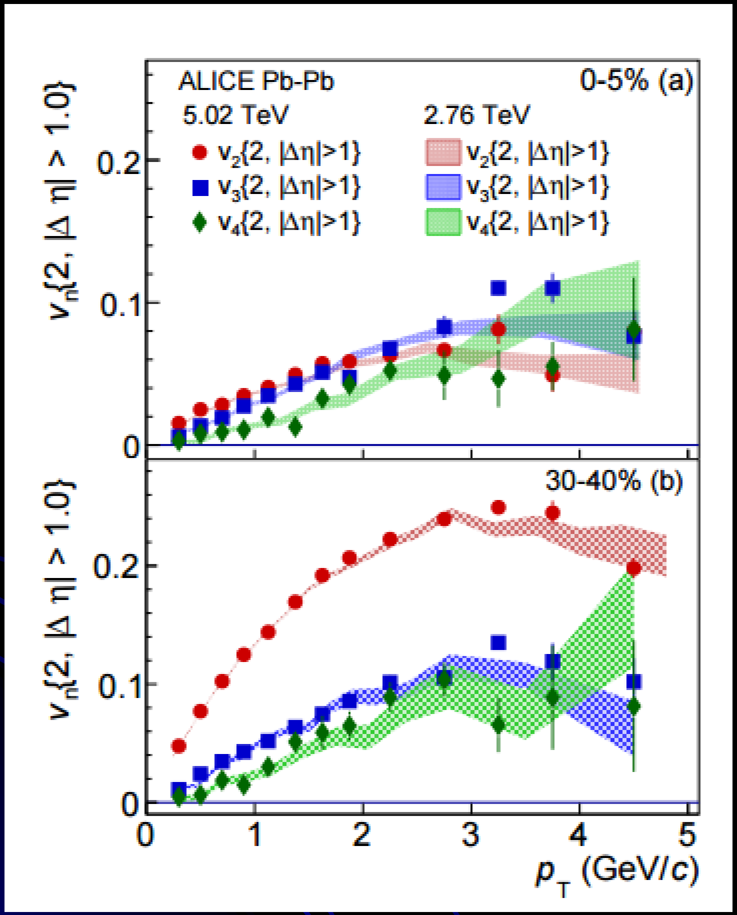


- The anisotropic flow coefficients v_2, v_3 and v_4 are found to increase by (3.0±0.6)%, (4.3±1.4)% and (10.2±3.8)%, respectively, in the centrality range 0-50%.
- None of the ratios 5.02 TeV/ 2.76 TeV of flow harmonics exhibit a significant centrality dependence in the centrality range 0–50%

arXiv:1602.01119 (accepted by PRL)

p_T dependence

arXiv:1602.01119 (accepted by PRL)

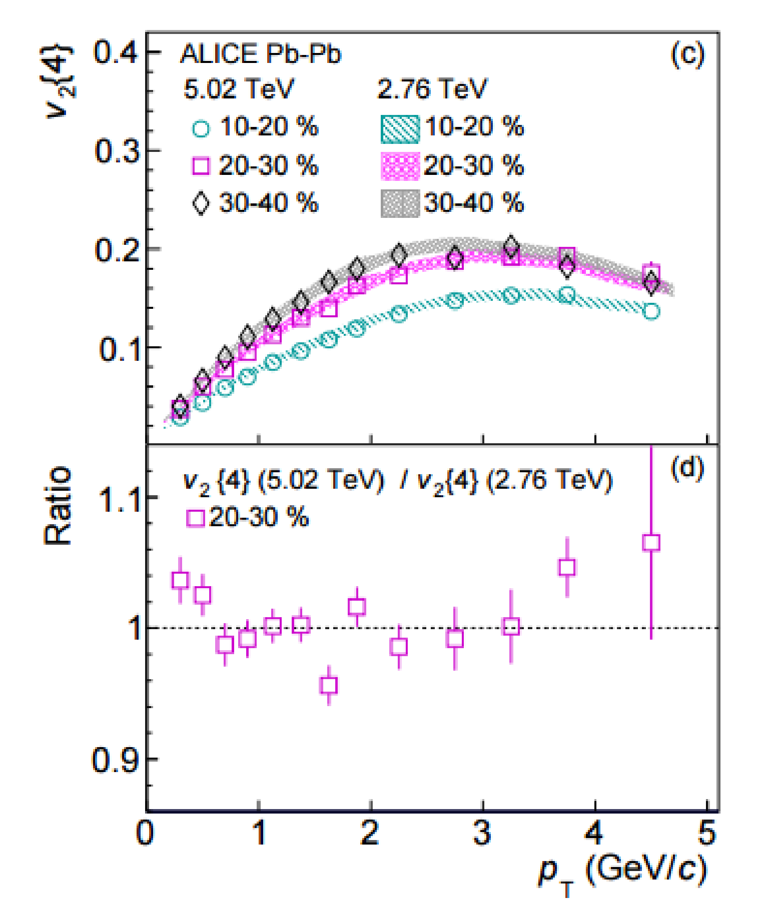


- For the 0–5% centrality class, at p_T > 2 GeV/*c* $v_3\{2\}$ is observed to become larger than $v_2\{2\}$, while $v_4\{2\}$ is compatible with $v_2\{2\}$
- For the 30–40% centrality class $v_2\{2\}$ is higher than $v_3\{2\}$ and $v_4\{2\}$ for the entire p_T range measured: no crossing

Comparable results to Run 1 results, increase in integrated flow can be attributed to the increase in mean transverse momentum

p_T dependence

arXiv:1602.01119 (accepted by PRL)

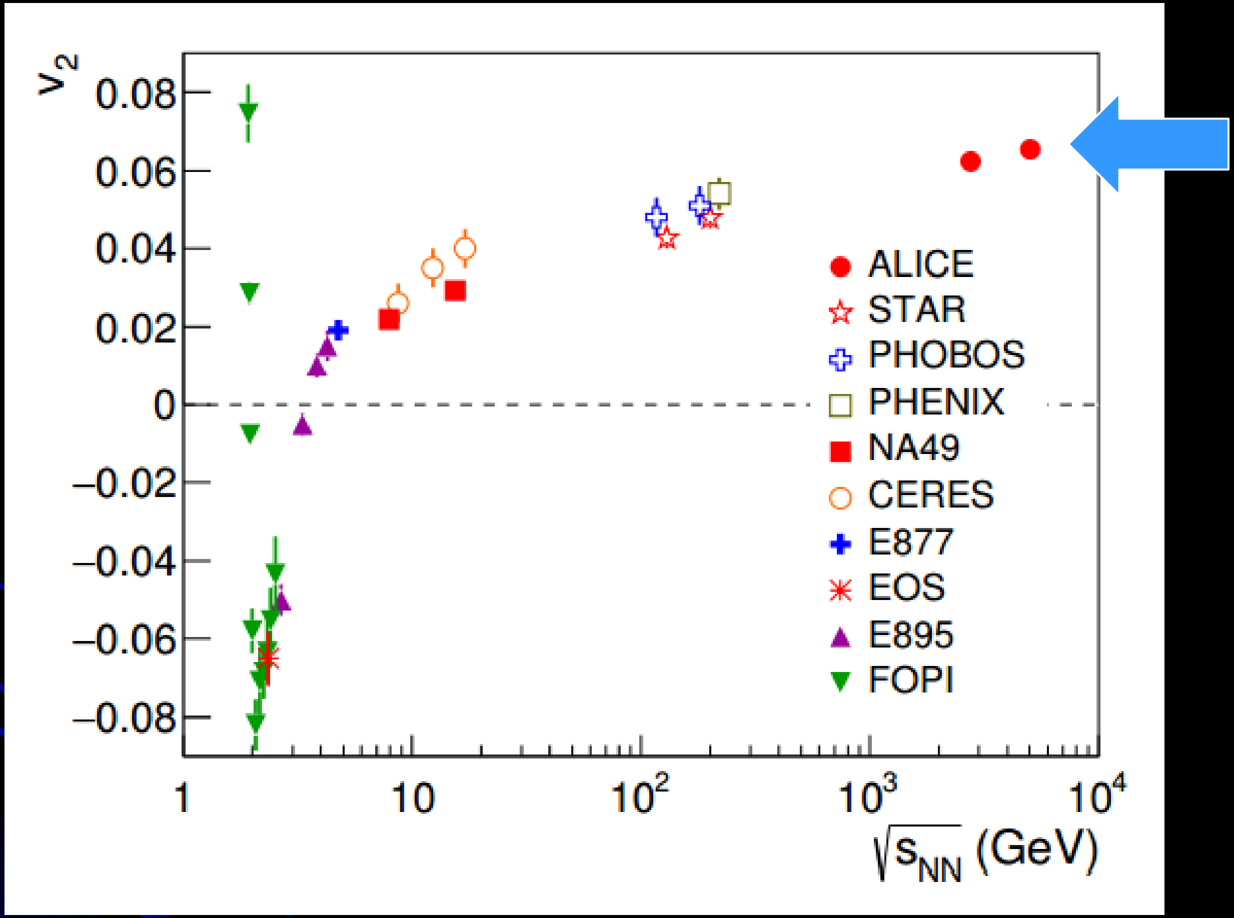


- The $v_2\{4\}$ decreases from mid-central to central collisions over the entire p_T range

Comparable results to Run 1 results, increase in integrated flow can be attributed to the increase in mean transverse momentum

Our mark in history

- ALICE Collaboration has measured the largest flow ever!



Outlook

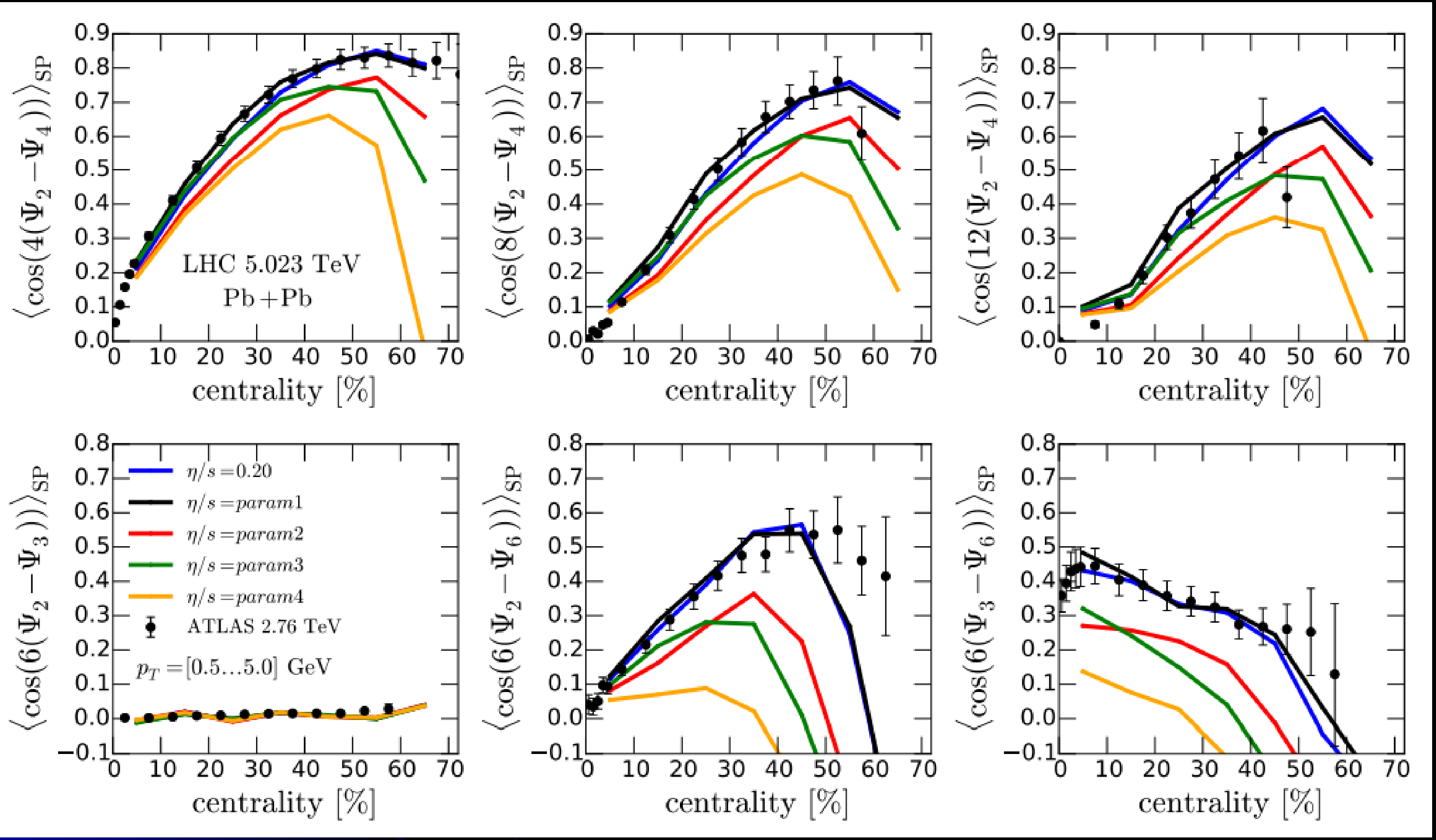
- Flow of identified particles
- Correlated v_n-v_m fluctuations
  - Disentangling initial conditions from system properties
- Higher order moments of higher flow harmonics
  - Feasible for the first time at Run 2
- Pinning down the temperature dependence of η/s

Thanks!

Backup slides

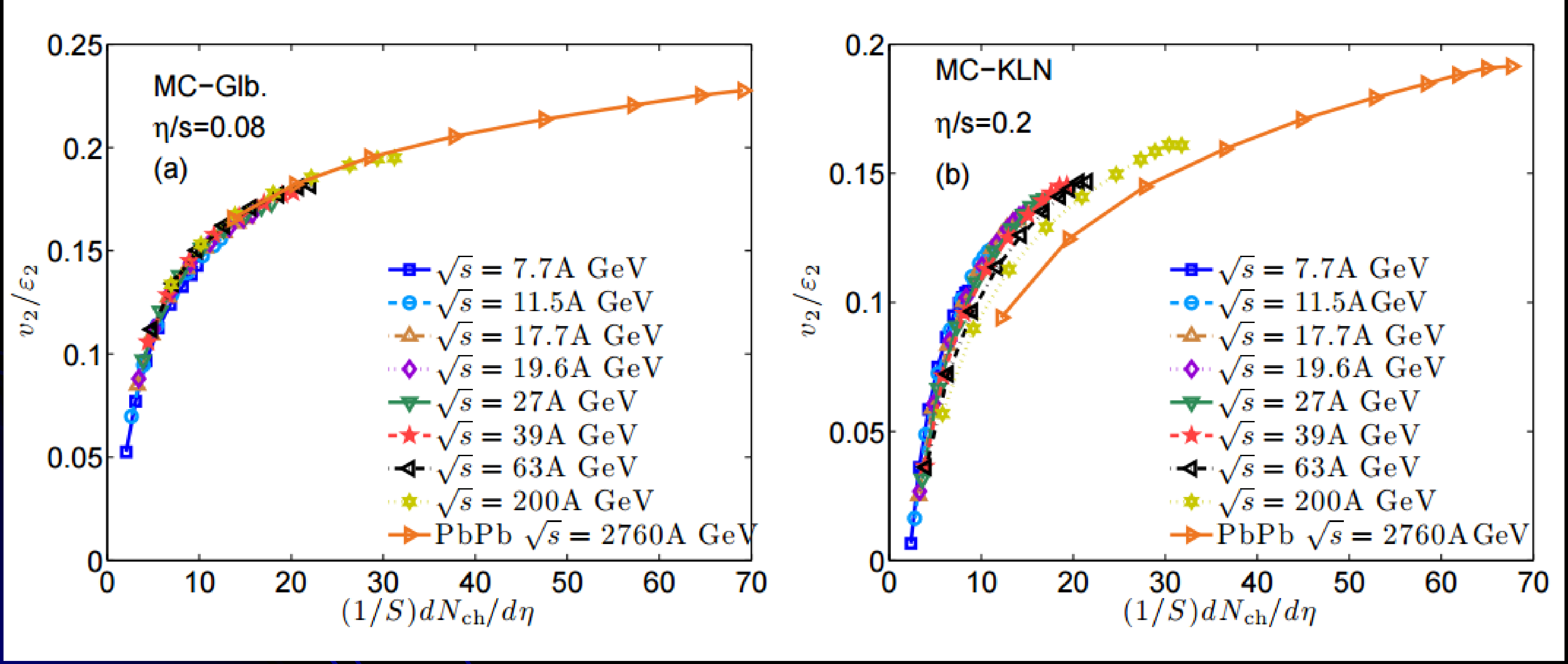
Symmetry planes at Run 2

- H. Niemi, K. J. Eskola, R. Paatelainen, and K. Tuominen, Phys. Rev. C 93, 014912 (2016) arXiv:1511.04296 [hep-ph]



Energy dependence

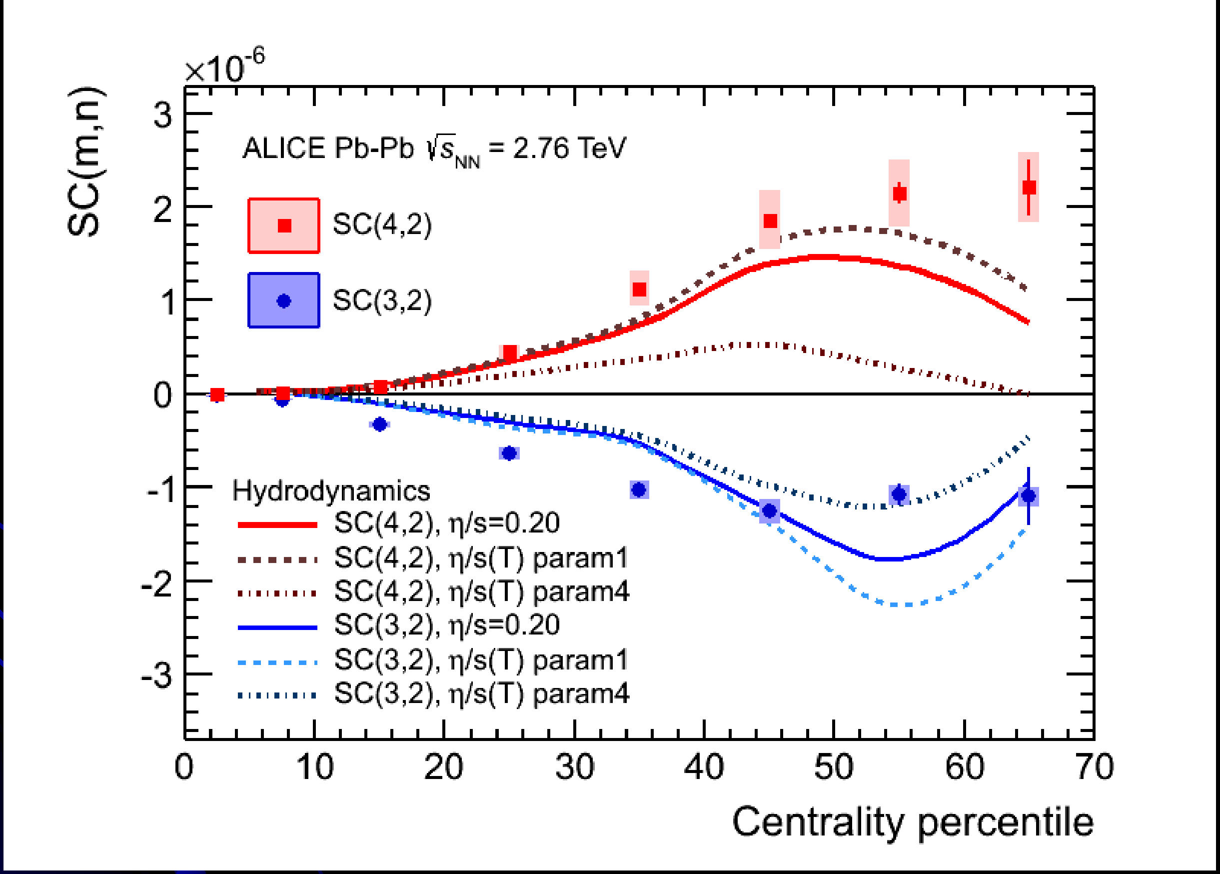
- C. Shen and U. Heinz, Phys. Rev. C85 (2012) 054902, arXiv:1202.6620



Only at LHC energies we see the difference in behavior between two models of initial conditions

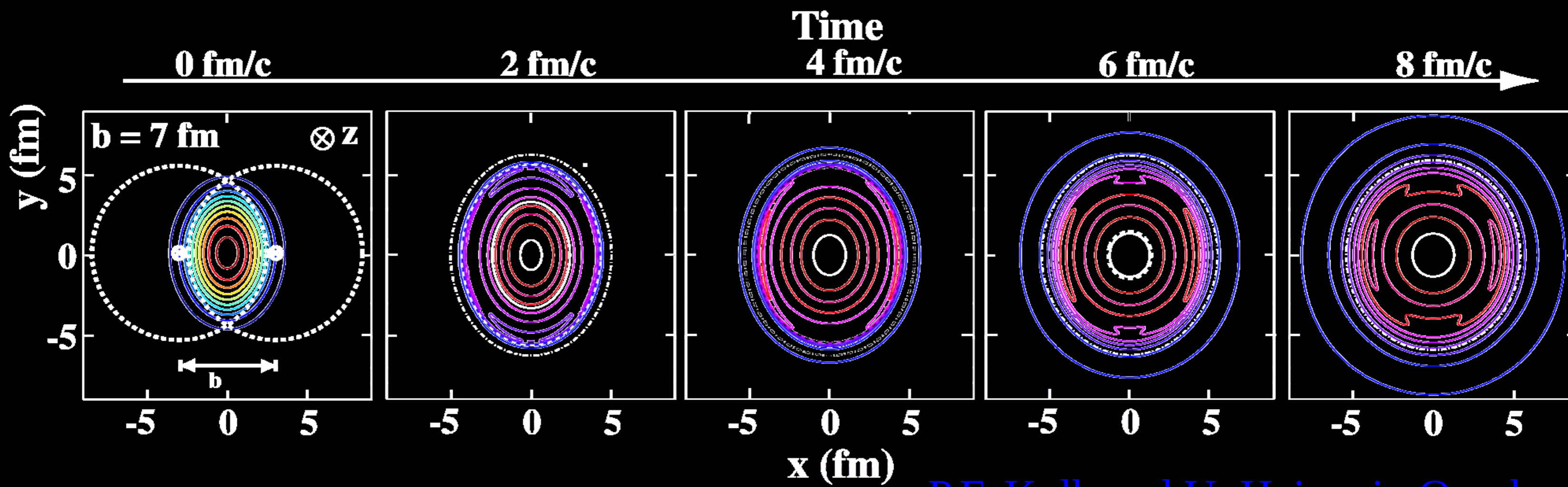
Symmetric Cumulants (SC)

- There is no a single centrality for which a given parametrization describe both SC(3,2) and SC(4,2)!

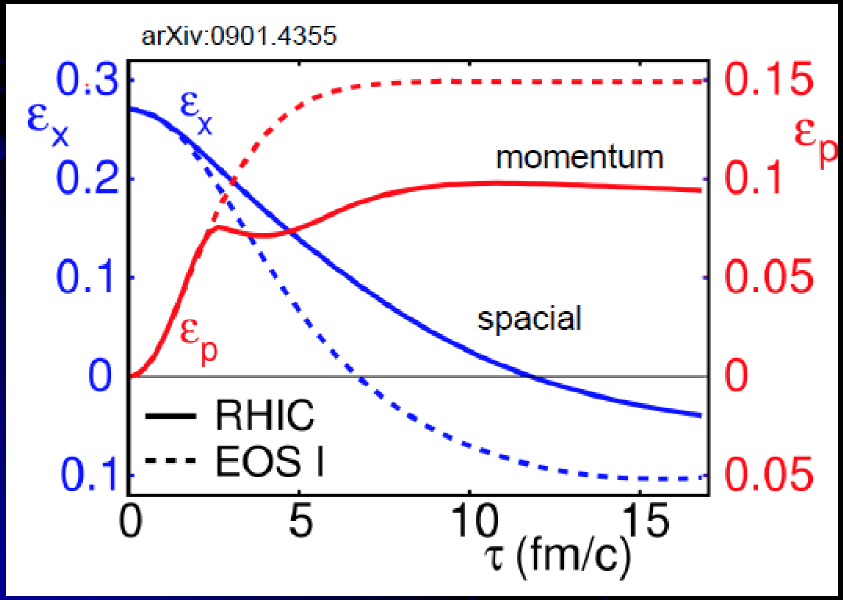


arXiv:1512.05397

Transfer of anisotropy



P.F. Kolb and U. Heinz, in Quark Gluon Plasma, nucl-th/0305084



As a function of time anisotropy in coordinate space decreases, while the anisotropy in momentum space increases

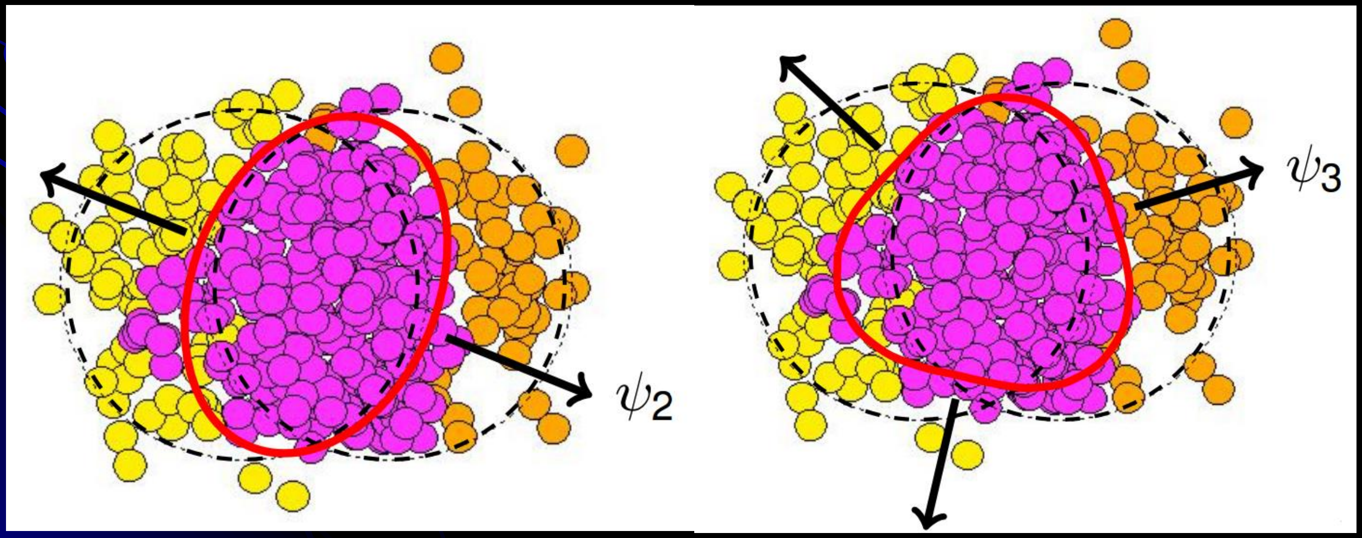
Fourier series

- We need a full Fourier decompositon to also take into account effects of fluctuations, each harmonic has its own symmetry plane:

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

$$f(\varphi) = \frac{1}{2\pi}\left[1 + 2\sum_{n=1} v_n \cos[n(\varphi - \Psi_n)]\right]$$

$$f(\varphi) = \frac{1}{2\pi}\left[1 + 2\sum_{n=1}^{\infty} (c_n \cos n\varphi + s_n \sin n\varphi)\right]$$



Correlations *vs.* Q-vectors

- Original idea is due to Sergei Voloshin:
  - **All multiparticle azimuthal correlations can be expressed analytically in terms of M-particle Q-vectors evaluated (in general) in different harmonics**
  - The major recent breakthrough in the world of multiparticle correlation techniques
- Initial analytic results for 2- and 4-p correlations:

$$\langle 2\rangle = \frac{|Q_n|^2 - M}{M(M-1)}$$

$$\langle 4\rangle = \frac{|Q_n|^4 + |Q_{2n}|^2 - 2\cdot\mathbf{Re}\left[Q_{2n}Q_n^*Q_n^*\right] - 4(M-2)\cdot|Q_n|^2}{M(M-1)(M-2)(M-3)} + \frac{2}{(M-1)(M-2)}$$

R. Snellings, S. Voloshin, AB, PRC 83, 044913 (2011)

Cumulants

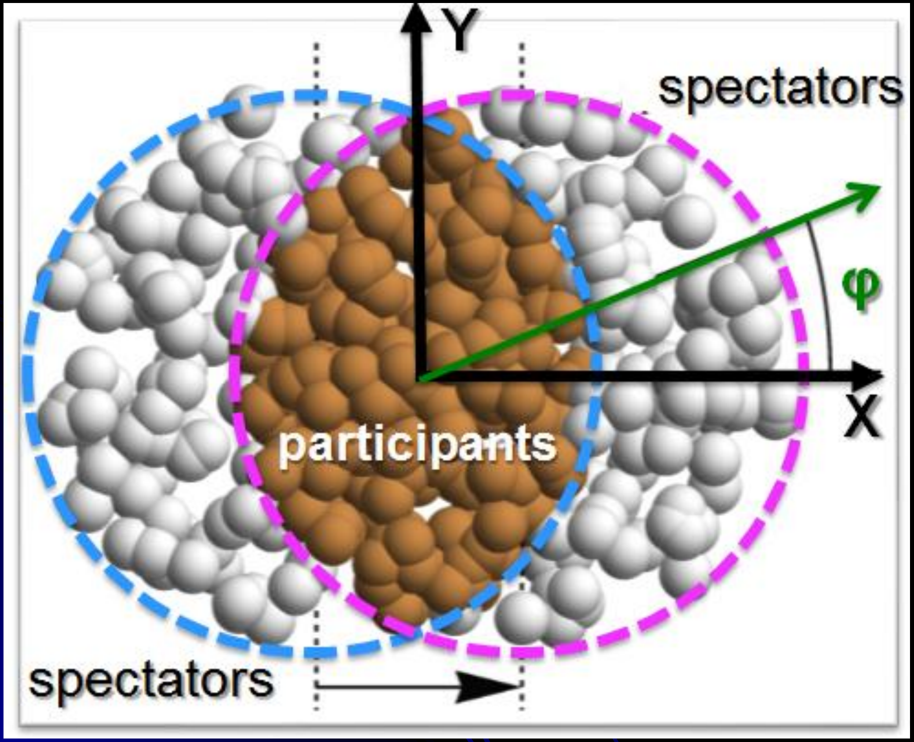
- Cumulants expressed in terms of azimuthal correlations:

$$
\begin{aligned}
QC\{2\} &= \langle\langle 2\rangle\rangle \\
QC\{4\} &= \langle\langle 4\rangle\rangle - 2\,\langle\langle 2\rangle\rangle^2 \\
QC\{6\} &= \langle\langle 6\rangle\rangle - 9\,\langle\langle 2\rangle\rangle\,\langle\langle 4\rangle\rangle + 12\,\langle\langle 2\rangle\rangle^3 \\
QC\{8\} &= \langle\langle 8\rangle\rangle - 16\,\langle\langle 6\rangle\rangle\,\langle\langle 2\rangle\rangle - 18\,\langle\langle 4\rangle\rangle^2 \\
&+ 144\,\langle\langle 4\rangle\rangle\,\langle\langle 2\rangle\rangle^2 - 144\,\langle\langle 2\rangle\rangle^4
\end{aligned}
$$

- In the case all correlations are expressed analytically in terms of *Q*-vectors => *Q*-cumulants (QC) (or direct cumulants)

Initial conditions

- **Eccentricities** quantify the initial anisotropic geometry formed by participating nucleons



- Simplest case: 'Ellipticity'

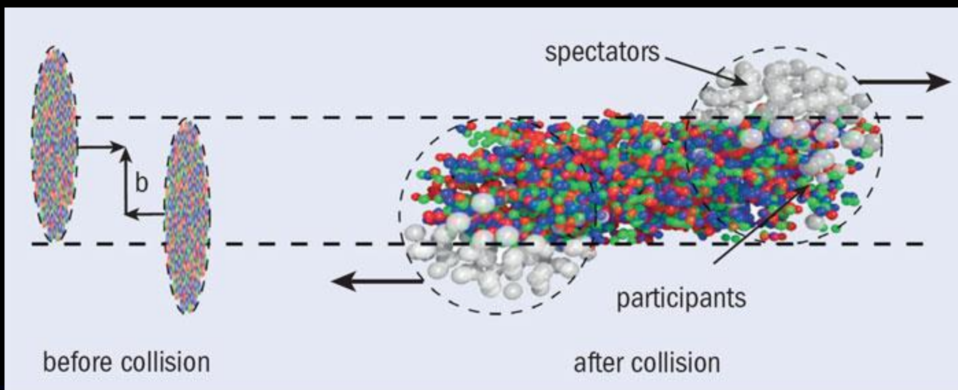
$$\varepsilon = \frac{\langle y^2 - x^2 \rangle}{\langle y^2 + x^2 \rangle}$$

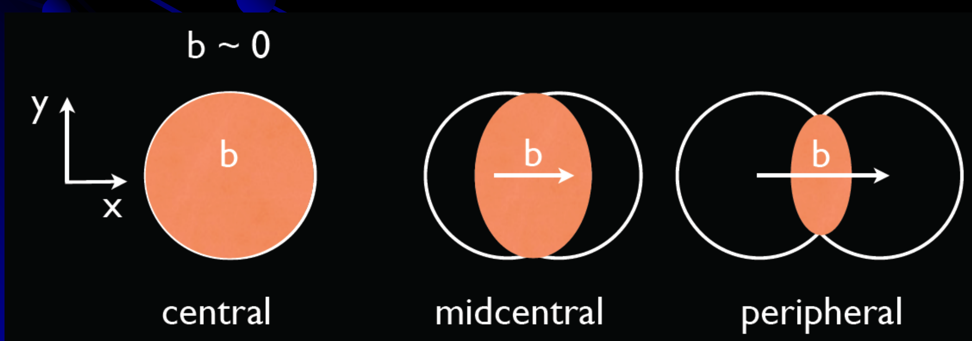
- General case:

$$\varepsilon_n = \frac{\sqrt{\langle r^n \cos(n\phi)\rangle^2 + \langle r^n \sin(n\phi)\rangle^2}}{\langle r^n \rangle}$$

Centrality

- (Almost) exclusively the heavy-ion concept





- **N_{part}** or **$N_{wounded}$**: number of nucleons which suffered at least one inelastic nucleon-nucleon collision
- **N_{coll}** or N_{bin}: number of inelastic nucleon-nucleon collisions