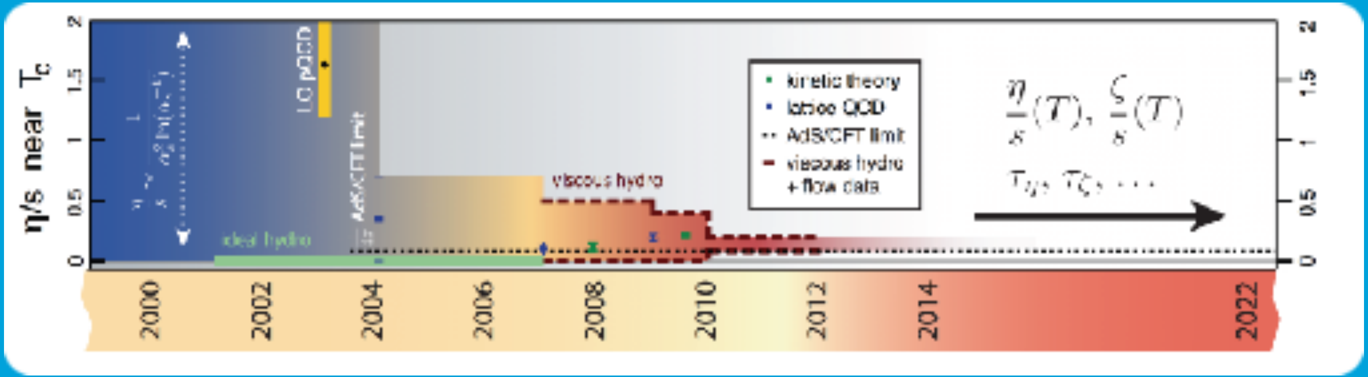
Probing QCD matter under extreme conditions: focus on anisotropic flow



Panos Christakoglou

Maastricht University and Nikhef

Panos.Christakoglou@maastrichtuniversity.nl

Probing QCD matter under extreme conditions: focus on anisotropic flow

Before starting…some needed disclaimers

- My intention is to illustrate the physical mechanisms and implications of some of the basic flow measurements
- The lecture is not mean to be an exhaustive list of the latest experimental results
  - Apologies if I didn’t include your own or your favourite flow result
- (Strong) personal bias in some of the topics is not excluded
  - I mainly use results from the LHC and from ALICE just because I can find the relevant plots easier
  - Similar (in some cases even identical) physics conclusions would be extracted from RHIC plots
- Be careful of my (peculiar) sense of humour
  - Or whatever that is…

Panos Christakoglou

Maastricht University and Nikhef

Panos.Christakoglou@maastrichtuniversity.nl

Matter under extreme conditions…

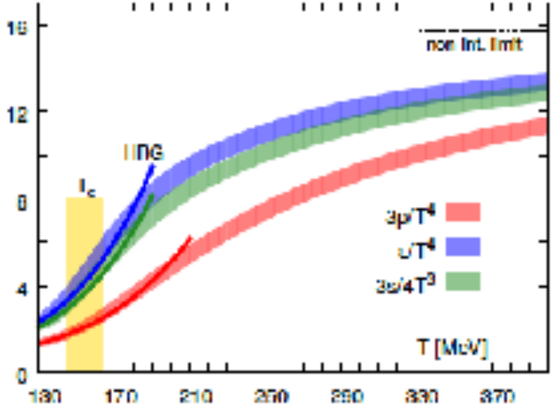
Fermi (~1953)

Hagedorn (~1965)

Lee-Wick abnormal matter (~1974)

QCD matter under extreme conditions

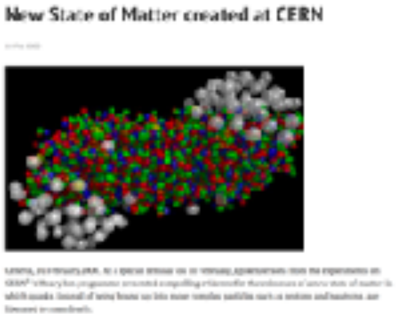
HotQCD Collaboration: Phys.Rev. **D90**, (2014) 094503



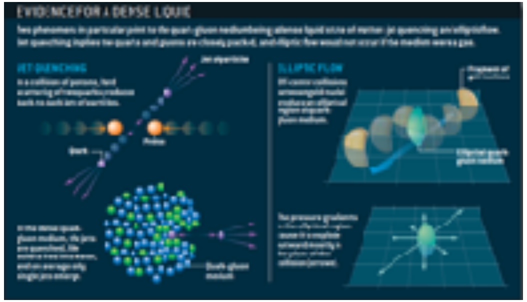
Shuryak
Quark Gluon
Plasma - QGP
(1978)

Series of experiments at:

- Bevalac (HI between 1980-1993)
- AGS (Si/Au beams ~1986-1994)
- SPS (S/Pb beams ~1987-Today)
- RHIC (Au beams, 2000-Today)
- LHC (Pb beams, 2010-Today)



- The Quark-Gluon Plasma (QGP):
  - a state of matter where the quarks and gluons are not confined in hadronic bags
  - existed few μs after the Big-Bang (the universe crossed this phase after expanding and cooling down): Studying the strong phase transition ➞ study primordial matter
- QCD: Phase transition beyond a critical temperature (~155 MeV i.e. 10^{12} degree) and energy density (~0.5 GeV/fm^3) ➞ accessible in the laboratory ➞ heavy-ion collisions

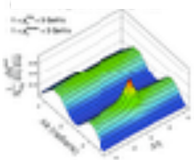
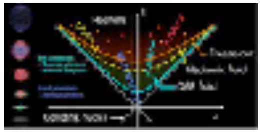
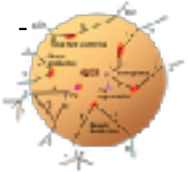
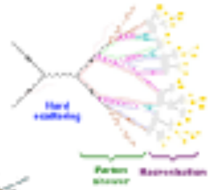


Heavy ion physics program

- Thermodynamics description of the medium, using macroscopic quantities
  - EoS, V, T, ε, η/s, …
- Understand the microscopic details of the matter formed
  - Can we resolve quarks and gluons as the degrees of freedom?
- Limit of QGP formation?
  - Can “QGP signals” be switched off vs multiplicity or system size?
- (non-QGP focused) QCD studies
  - Parity violation in strong interactions
  - Magnetic field studies
  - Strong interaction potentials
  - …

Some of the phenomena we focus on…

Collective flow | Thermal radiation | Quenching effects | CME

Small systems e.g. pp, p-Pb, O-O


vs

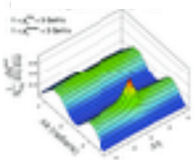
Heavy ion physics program

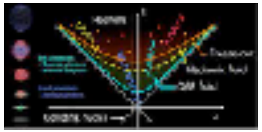
Need to study many observables as a function of centrality

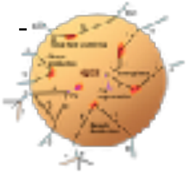
- Thermodynamics description of the medium, using macroscopic quantities
  - EoS, V, T, ε, η/s, …
- Understand the microscopic details of the matter formed
  - Can we resolve quarks and gluons as the degrees of freedom?
- Limit of QGP formation?
  - Can “QGP signals” be switched off vs multiplicity or system size?
- (non-QGP focused) QCD studies
  - Parity violation in strong interactions
  - Magnetic field studies
  - Strong interaction potentials
  - …

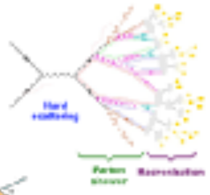
Some of the phenomena we focus on…

Collective flow
Quenching effects
Thermal radiation
CME





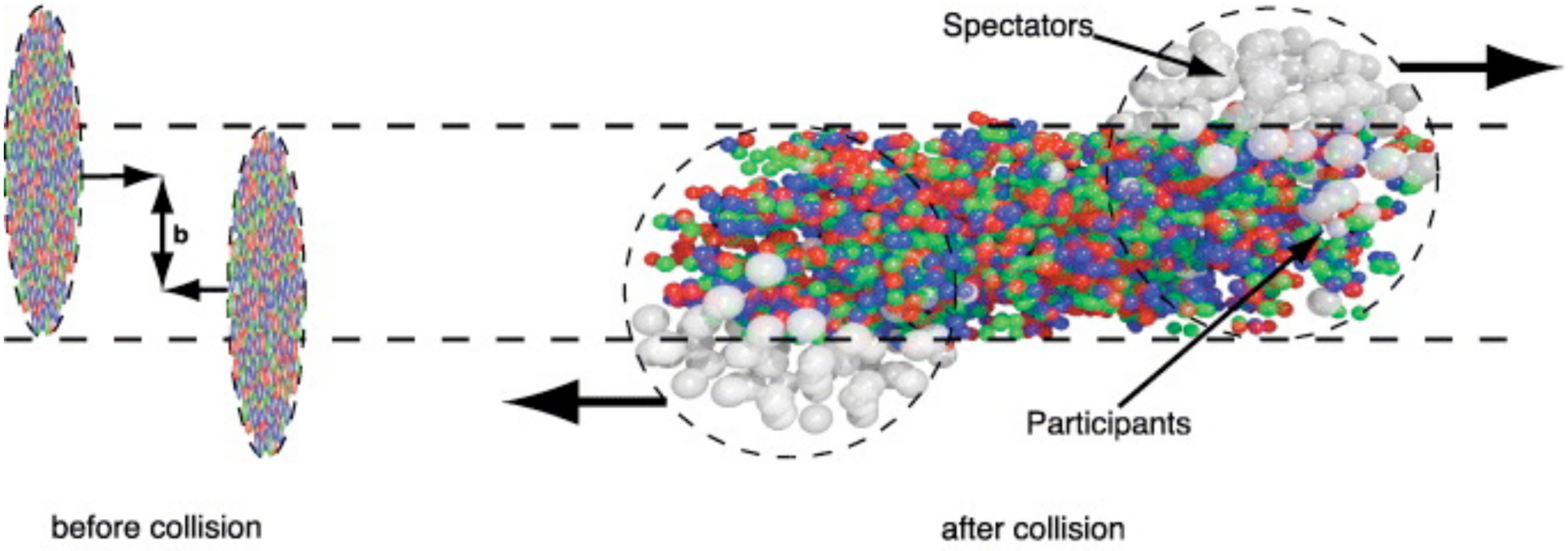




Small systems e.g. pp, p-Pb, O-O

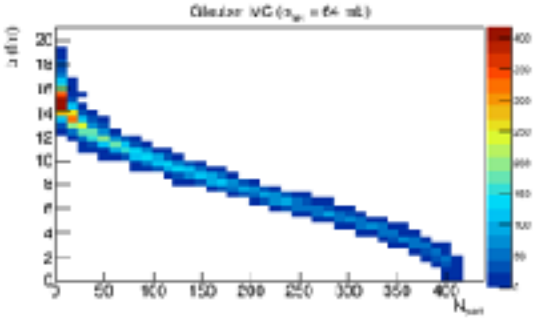
VS

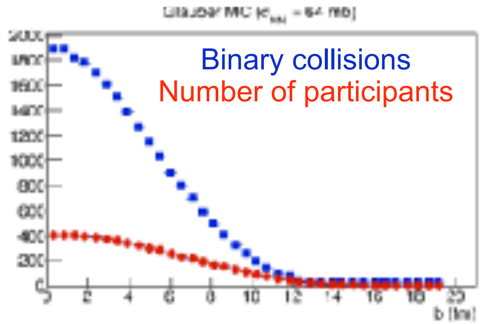
Centrality in heavy ion collisions



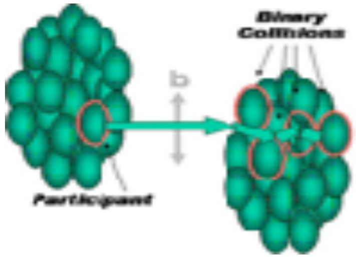
Number of participants/spectators

- Number of participants (N_{part}): nucleons undergoing at least one collision
  - Scale with volume ~2A
- Number of binary collisions (N_{coll}): inelastic collisions between a nucleon of one nucleus and at least one nucleon of the other nucleus
  - Scale with $AxA^{1/3}=A^{4/3}$
- Number of spectators (N_{spec}): nucleons that do not lie in the overlap region and thus fly away without interacting



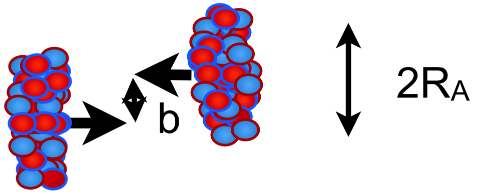


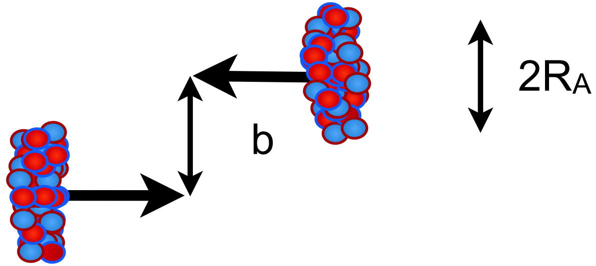
Ann.Rev.Nucl.Part.Sci.57,2007



Defining centrality: impact parameter

- Heavy ions are not point-like objects
  - Collisions can create systems with different properties depending on whether they are head-on (i.e. large overlap region) or if the nuclei graze each other (i.e. small overlap region)
  - Centrality defined geometrically by the impact parameter b
    - Distance between the centres of the two nuclei
    - Perpendicular to the beam axis
  - Centrality related to the fraction of the geometrical cross-section that overlaps
    - proportional to $\pi b^2/\pi(2R_A)^2$
- Experimentally centrality defined from particle multiplicity or energy deposited in (forward) detectors

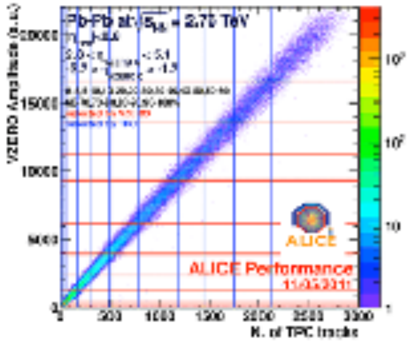


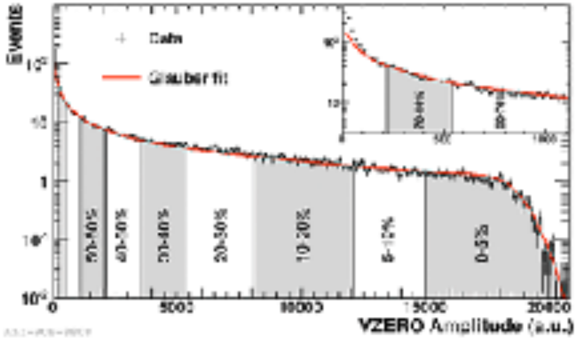


Gauging centrality experimentally

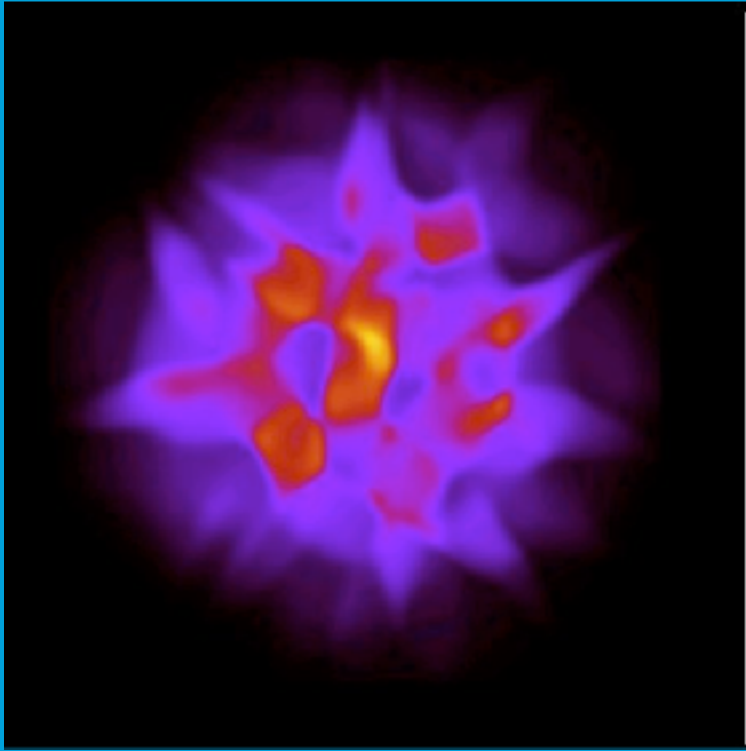
- Experimentally neither the impact parameter nor the N_{part}/N_{spec} can be measured
  - Have to rely on experimental measurements:
    - Multiplicity (central or/and forward regions)
      - Large (small) for central (peripheral) collisions
    - Zero degree calorimeters (energy deposited by spectator nucleons)
      - E_{ZDC} small (large) for central (peripheral) collisions
  - Expressed as the percentage of the total nuclear interaction cross section
    - e.g. 5% most central Pb-Pb (or Au-Au) collisions are the 5% with the highest multiplicity

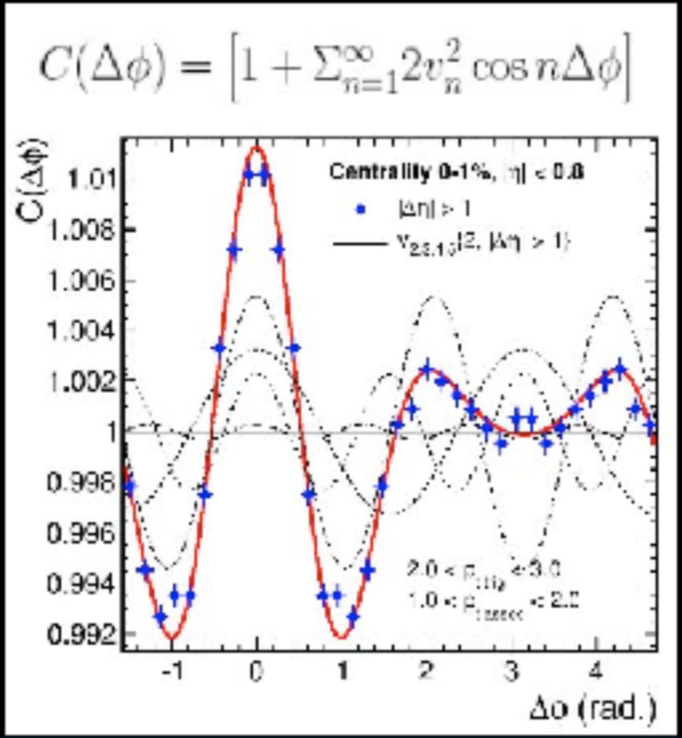
(ALICE Collaboration)
Phys. Rev. C88 (2013) 044909





Anisotropic flow

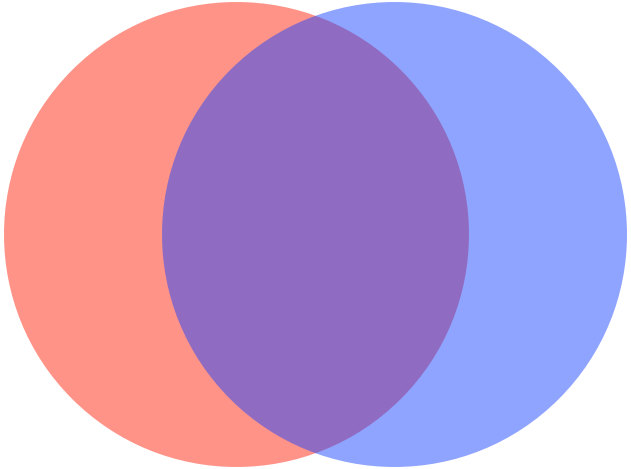




Panos.Christakoglou@maastrichtuniversity.nl

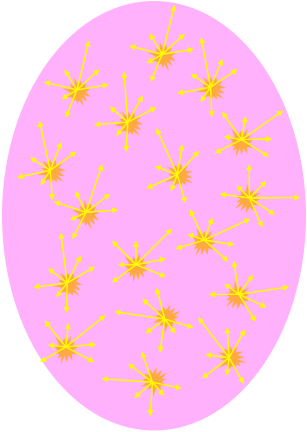
To flow or not to flow?

To flow or not to flow?



To flow or not to flow?

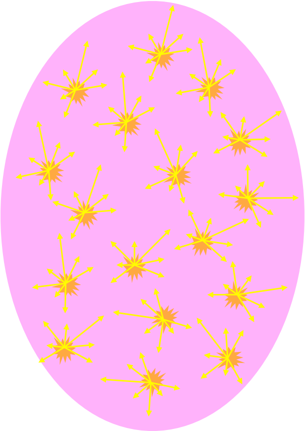
Superposition of independent pp collisions



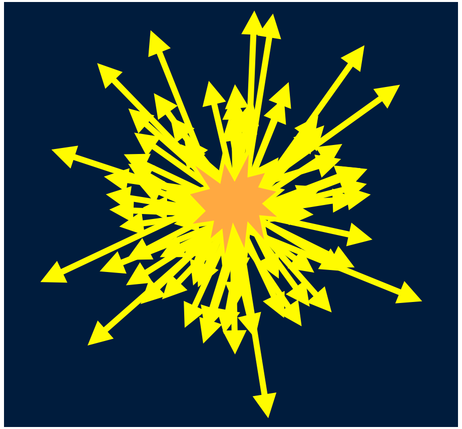
$$\epsilon = \frac{\langle y^2 - x^2 \rangle}{\langle y^2 + x^2 \rangle}$$

To flow or not to flow?

Superposition of independent pp collisions



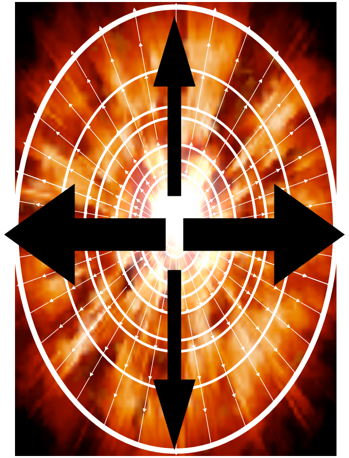
Momenta pointing at random directions relative to the reaction plane



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

To flow or not to flow?

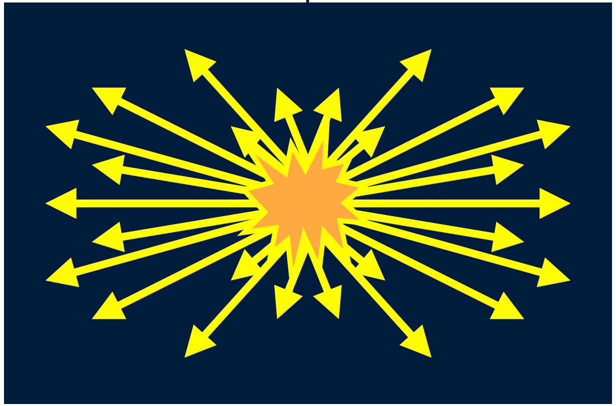
Evolution as a bulk system



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

Pressure gradient higher in-plane i.e. pushes bulk out: flow

More and faster particles in-plane than out-of-plane



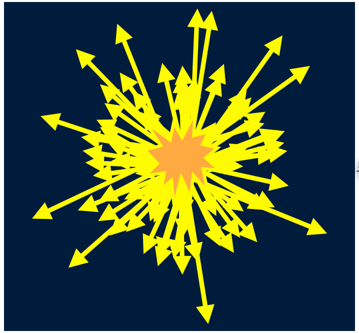
Development as a bulk system: high density and pressure at the centre of the fireball

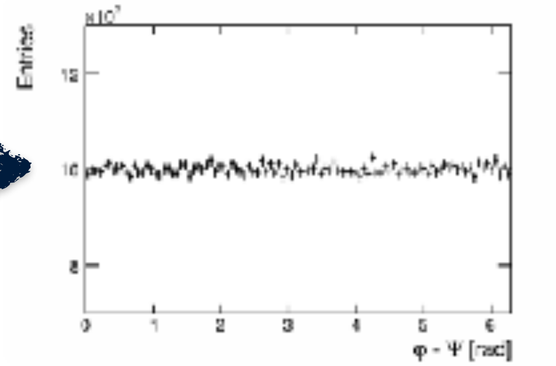
Asymmetric pressure gradients (larger in-plane than out-of-plane) push bulk out → flow

Elliptic flow

Elliptic flow

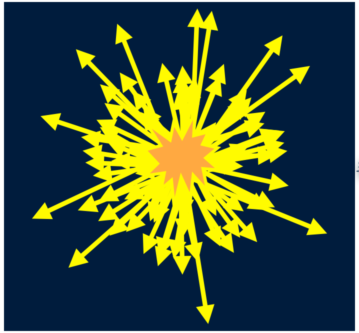
Superposition of independent pp collisions

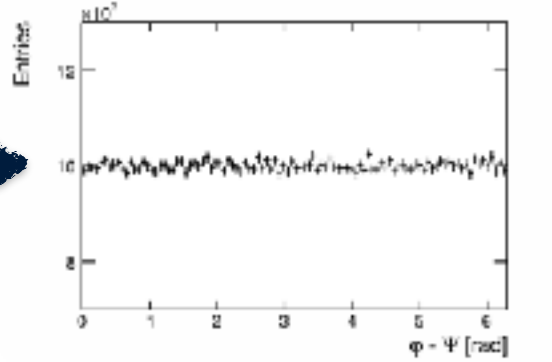




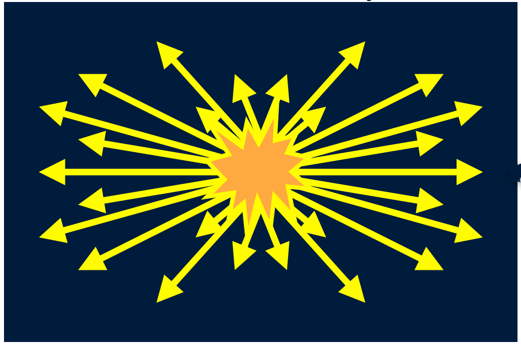
Elliptic flow

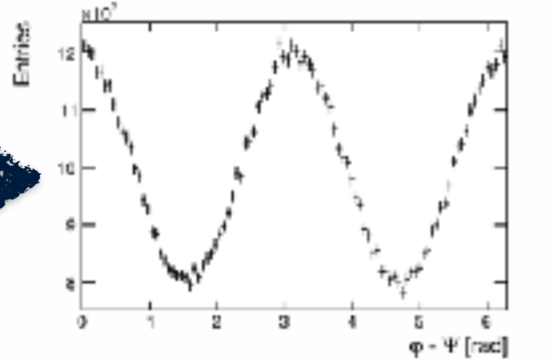
Superposition of independent pp collisions





Evolution as a bulk system

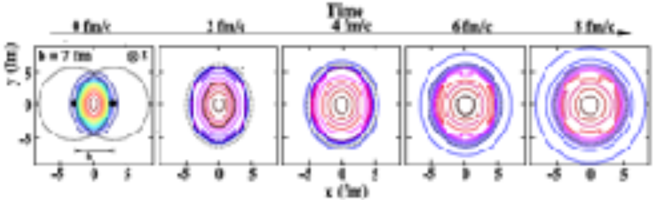




Panos.Christakoglou@maastrichtuniversity.nl

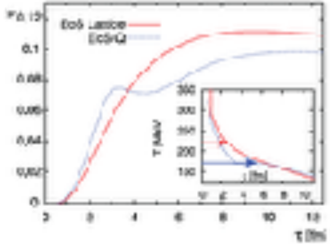
Coordinate space vs momentum anisotropies

Coordinate space: eccentricities



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

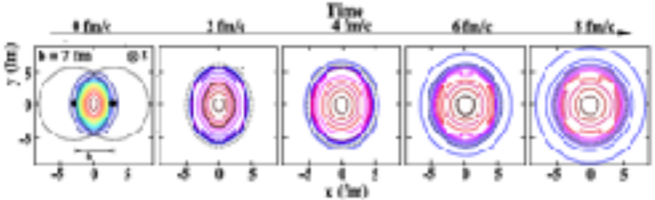
Momentum space: flow harmonics



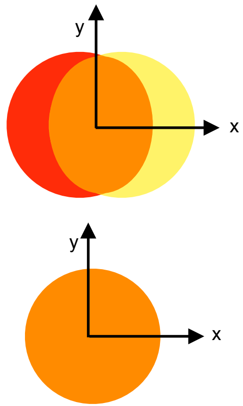
$$\epsilon_P = \frac{\langle T_{xx} - T_{yy} \rangle}{\langle T_{xx} + T_{yy} \rangle}$$

Coordinate space vs momentum anisotropies

Coordinate space: eccentricities

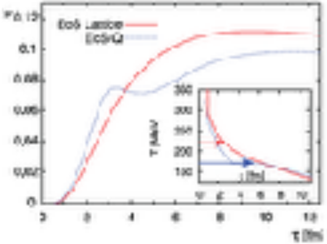


$$\epsilon = \frac{\langle y^2 - x^2 \rangle}{\langle y^2 + x^2 \rangle}$$

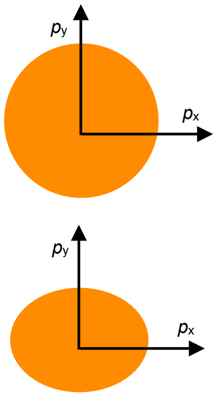


time

Momentum space: flow harmonics

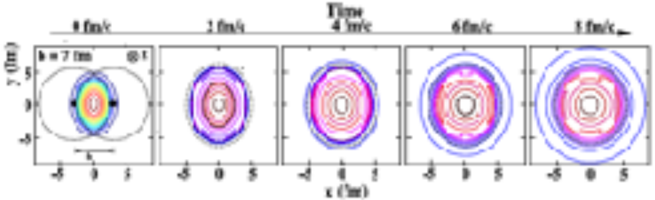


$$\epsilon_P = \frac{\langle T_{xx} - T_{yy} \rangle}{\langle T_{xx} + T_{yy} \rangle}$$

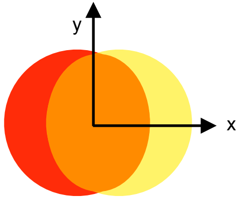


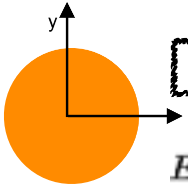
Coordinate space vs momentum anisotropies

Coordinate space: eccentricities



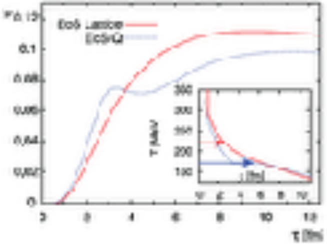
$$\epsilon = \frac{\langle y^2 - x^2 \rangle}{\langle y^2 + x^2 \rangle}$$



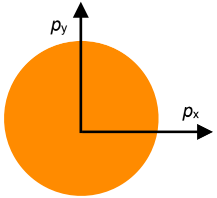


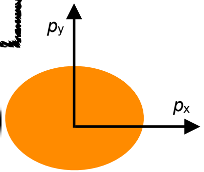
time

Momentum space: flow harmonics



$$\epsilon_P = \frac{\langle T_{xx} - T_{yy} \rangle}{\langle T_{xx} + T_{yy} \rangle}$$





S. Voloshin and Y. Zhang, Z. Phys. **C70**, 665 (1996)

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

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

Connection to equation of state and to the system's transport properties (e.g. η/s, ζ/s)

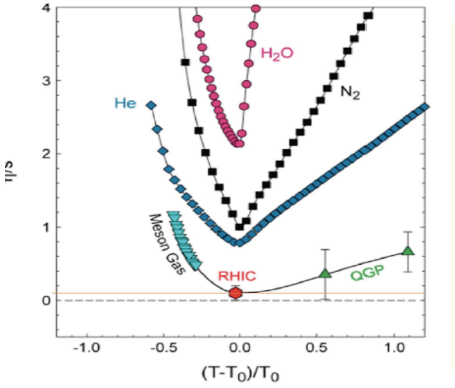
The perfect liquid at RHIC and LHC

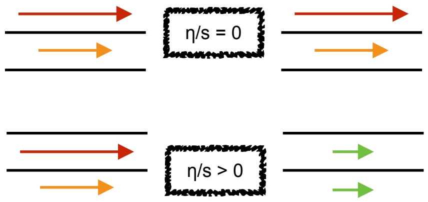

nature

Early Universe was a liquid

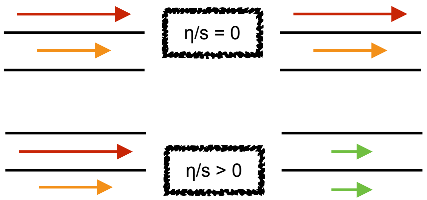

RHIC

RHIC Scientists Serve Up "Perfect" Liquid

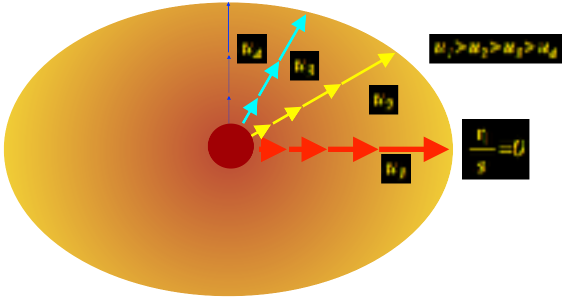




The perfect liquid at RHIC and LHC

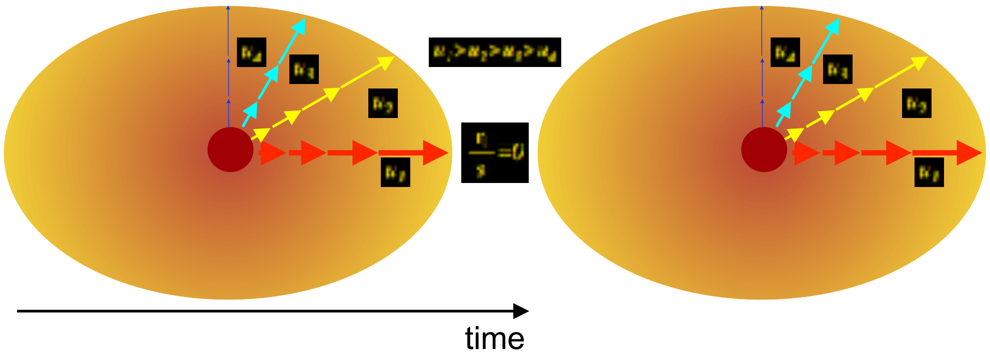


Specific shear viscosity



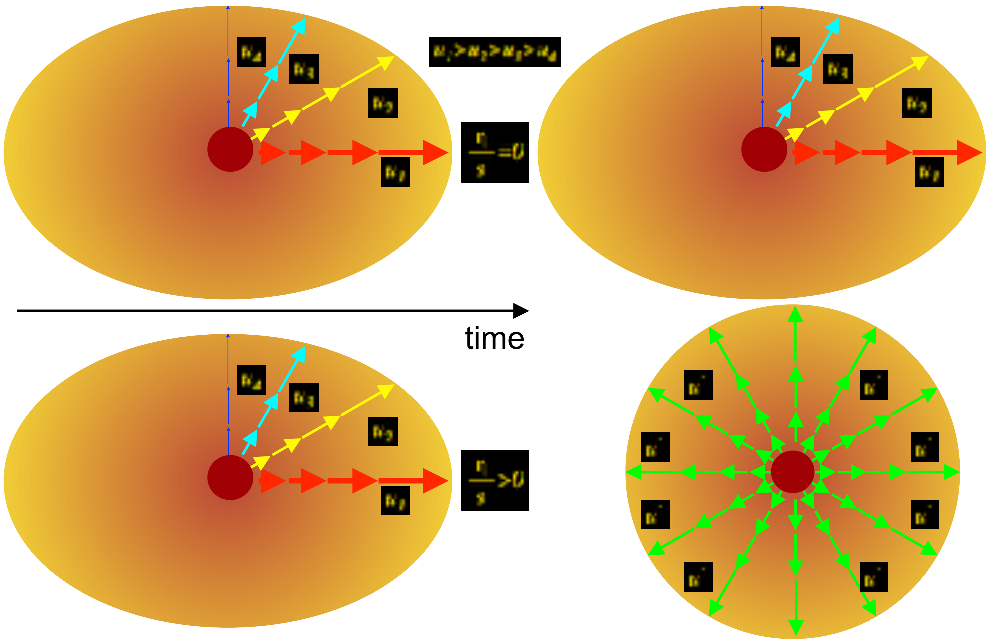
Specific shear viscosity

Large values of v_2



Specific shear viscosity

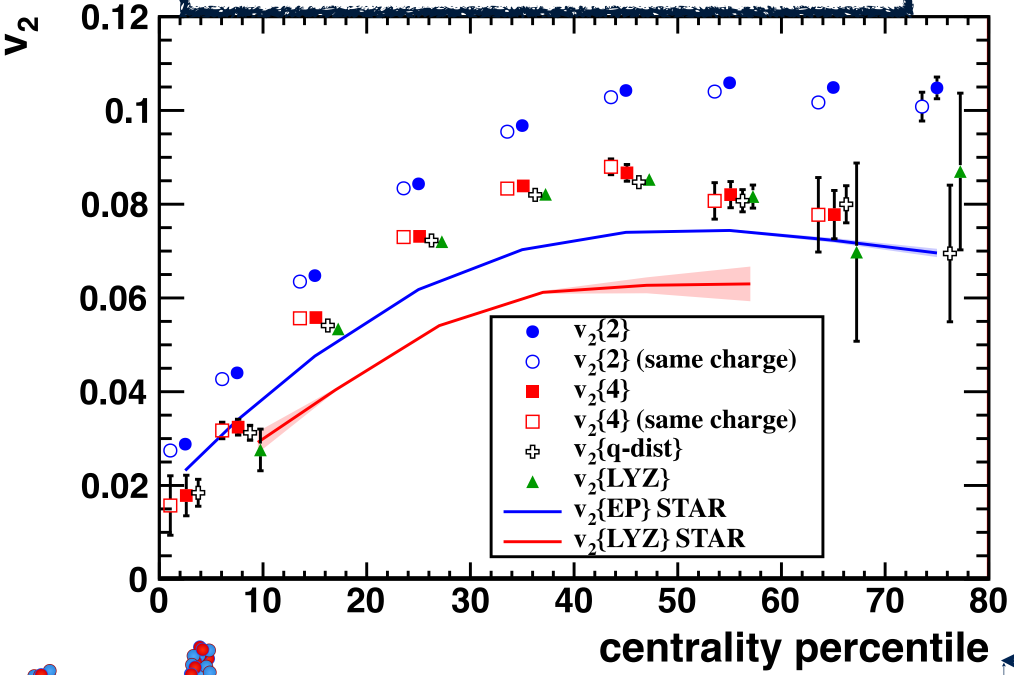
Large values of v_2

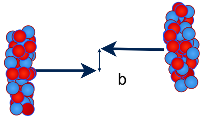


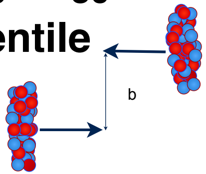
Small values of v_2

Elliptic flow @ LHC

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

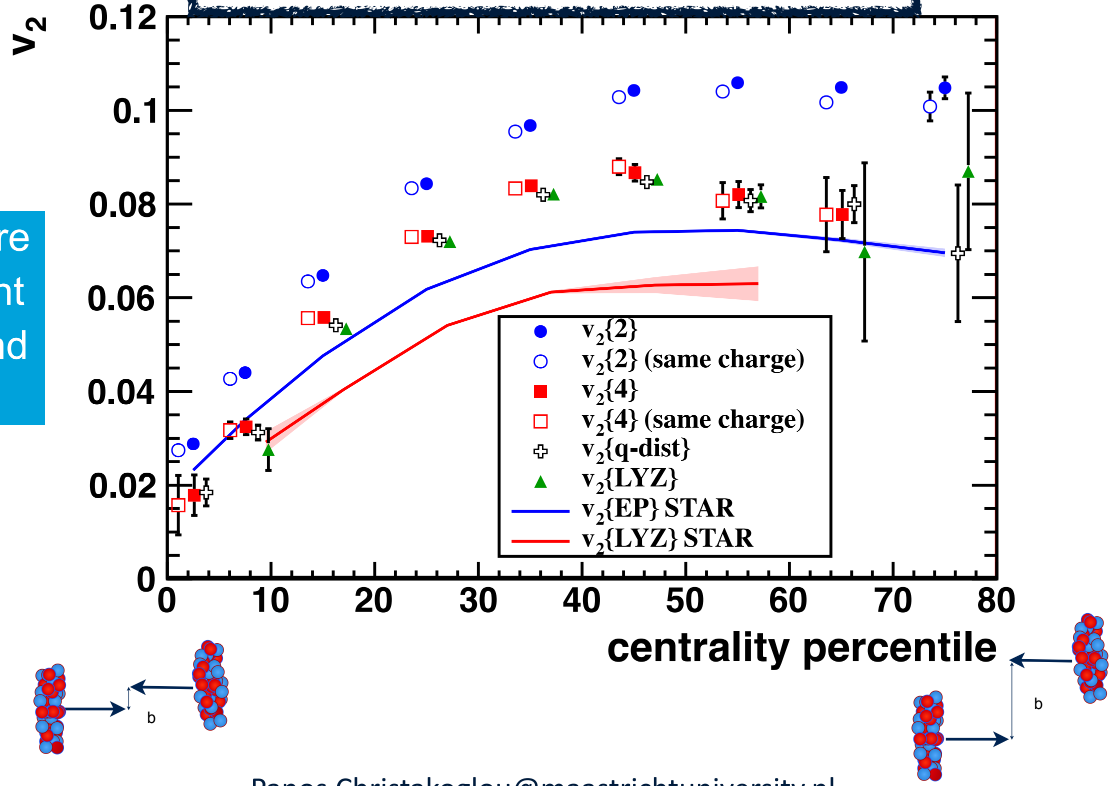






Elliptic flow @ LHC

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



Different methods are affected in a different way by **non-flow** and **flow fluctuations**

Non-flow contributions

- Correlations not connected to the common symmetry plane
  - resonances, jets, HBT,…
- Suppression (but not elimination) of non-flow using
  - multi-particle correlation techniques,
  - η-gap analyses,
  - different charge combinations,…

2-particle correlations

$$c_n\{2\} = \langle v_n^2 \rangle + \delta_2$$

$$\delta_2 \propto 1/M \Rightarrow v_n \gg 1/\sqrt{M}$$

4- (multi-) particle correlations

$$c_n\{4\} = \langle\langle 4 \rangle\rangle - 2\langle\langle 4 \rangle\rangle^2 =$$

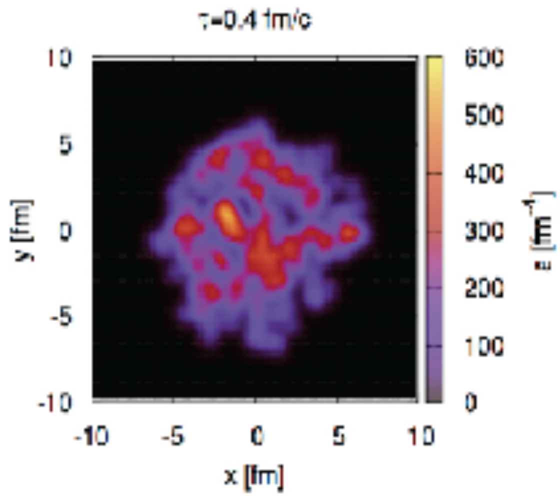
$$\langle v_n^4 \rangle + 4\langle v_n^2 \rangle \delta_2 + 2\delta_2^2 - 2(\langle v_n^2 \rangle + \delta_2)^2 + \delta_4 =$$

$$-\langle v_n^4 \rangle + \delta_4$$

$$\delta_4 \propto 1/M^3 \Rightarrow v_n \gg 1/M^{3/4}$$

Flow fluctuations

- Originating from the fluctuations in the initial collision geometry.
  - Fluctuations of initial energy/ pressure distributions lead to “irregular” shapes that fluctuate event-by-event



$$v_2\{2\} = \sqrt{\langle v_2^2\rangle} = ... = \langle v_2\rangle + \frac{1}{2}\frac{\sigma^2}{\langle v_2\rangle}$$

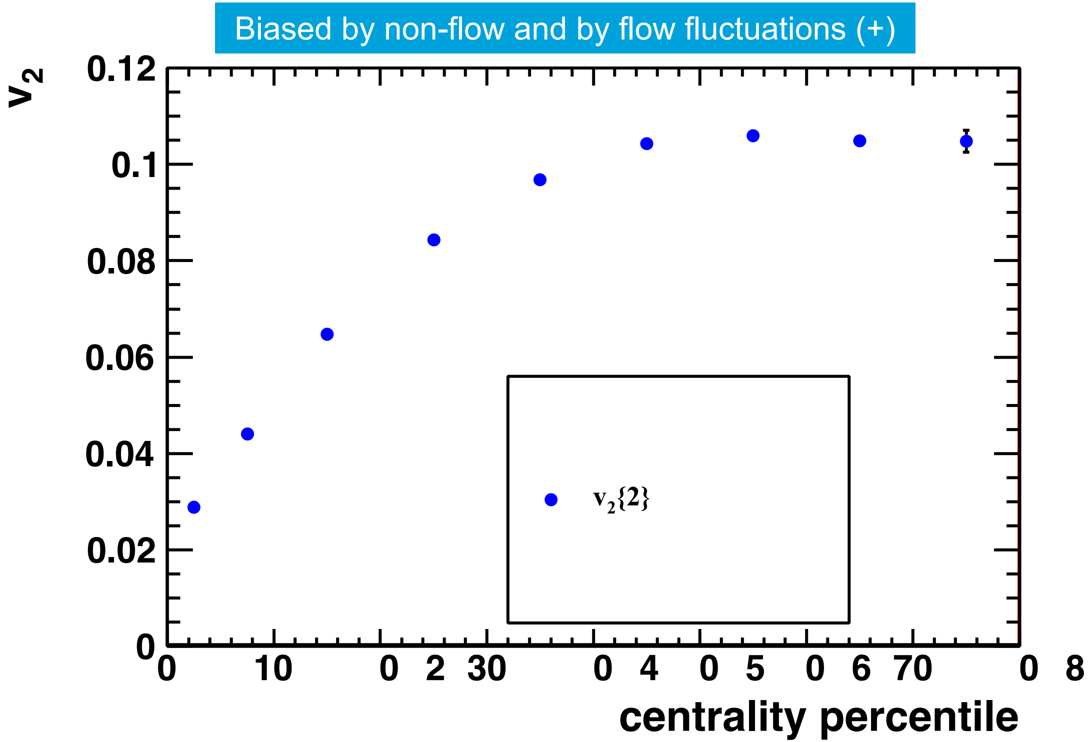
$$v_2\{4\} = \sqrt[4]{2\langle v_2^2\rangle - \langle v_2^4\rangle} = ... = \langle v_2\rangle - \frac{1}{2}\frac{\sigma^2}{\langle v_2\rangle}$$

$$v_2\{6\} = \sqrt[6]{\frac{1}{4}\left(\langle v_2^6\rangle - 9\langle v_2^2\rangle\langle v_2^4\rangle + 12\langle v_2^2\rangle^3\right)} = ... = \langle v_2\rangle - \frac{1}{2}\frac{\sigma^2}{\langle v_2\rangle}$$

2-particle correlation results

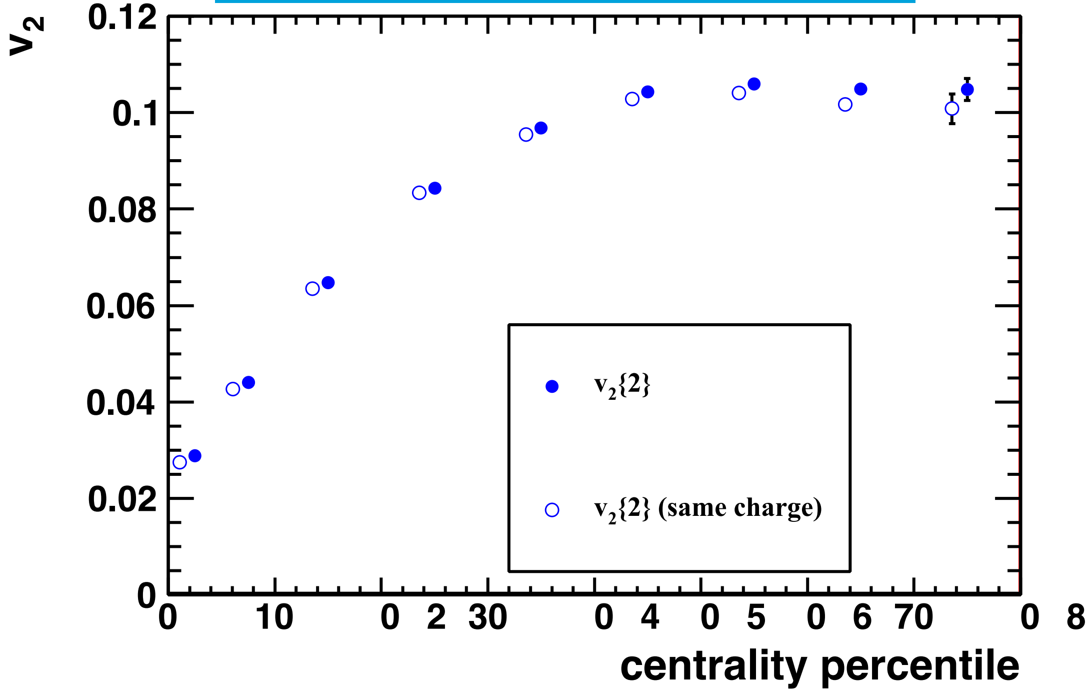
Biased by non-flow and by flow fluctuations (+)

2-particle correlation results



2-particle correlation results

Biased by non-flow and by flow fluctuations (+)

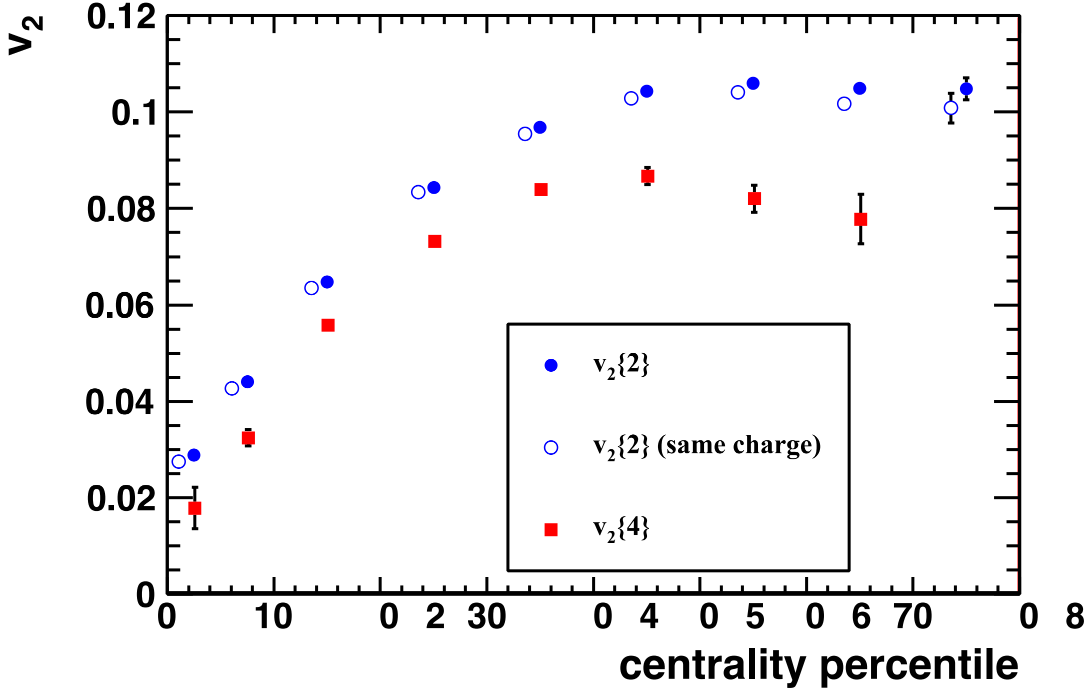


2- vs multi-particle correlation results

Suppresses non-flow (2p) but biased by flow fluctuations (-)

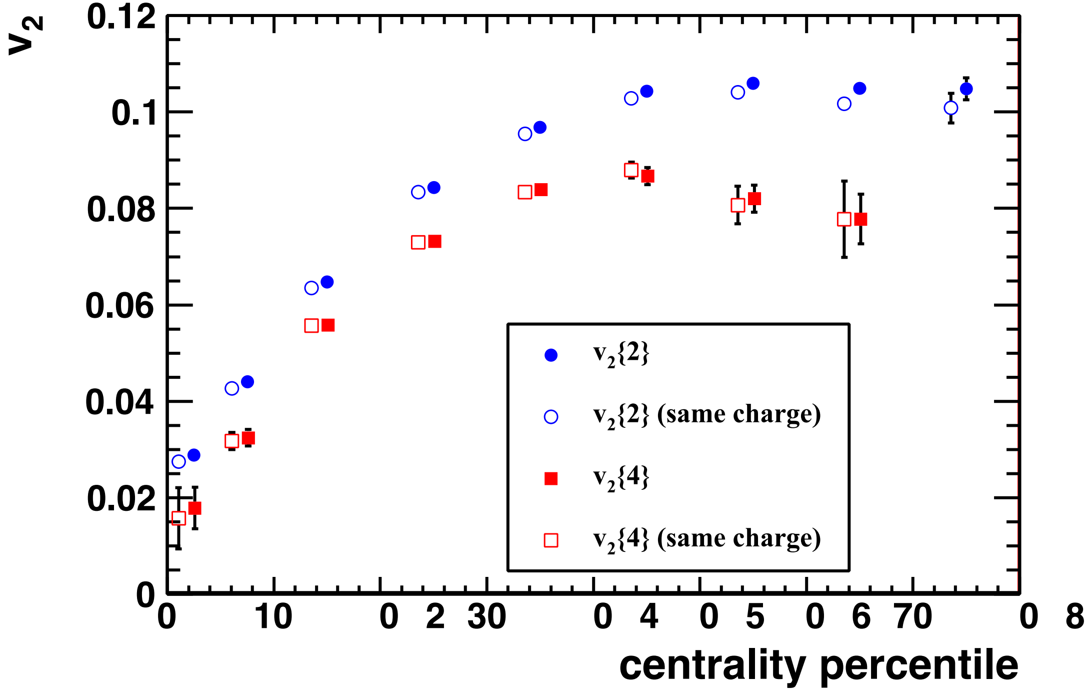
2- vs multi-particle correlation results

Suppresses non-flow (2p) but biased by flow fluctuations (-)



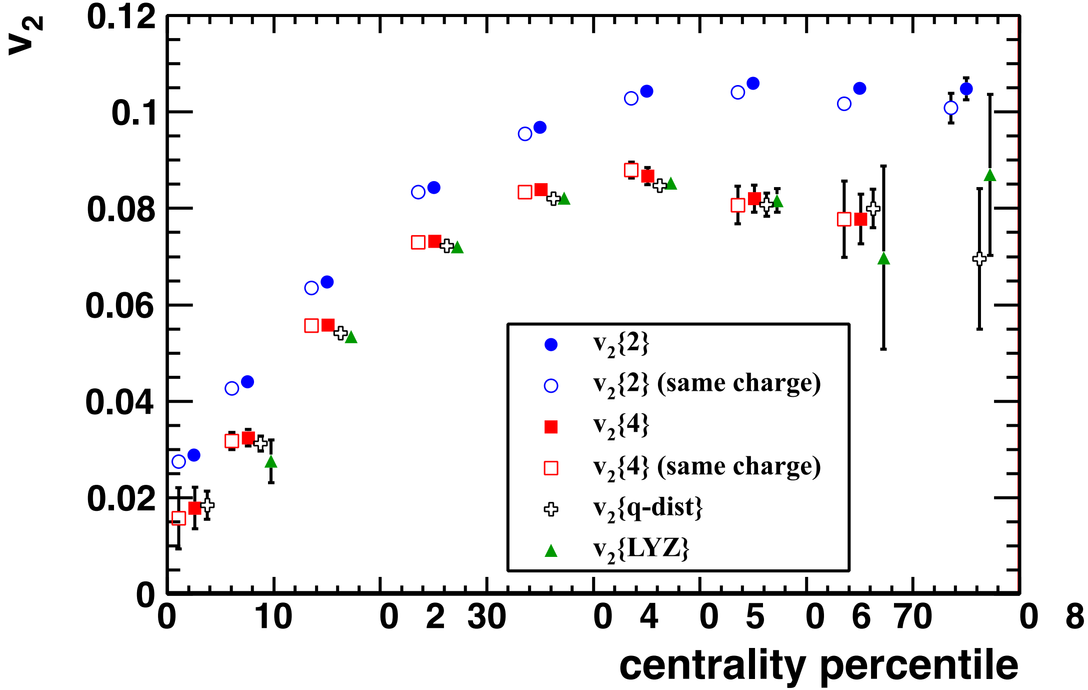
2- vs multi-particle correlation results

Suppresses non-flow (2p) but biased by flow fluctuations (-)



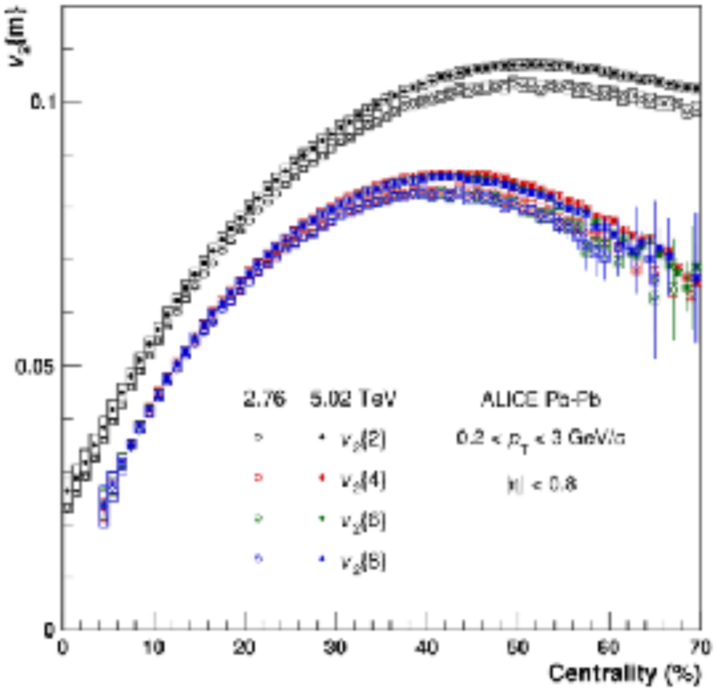
2- vs multi-particle correlation results

Suppresses non-flow (2p) but biased by flow fluctuations (-)



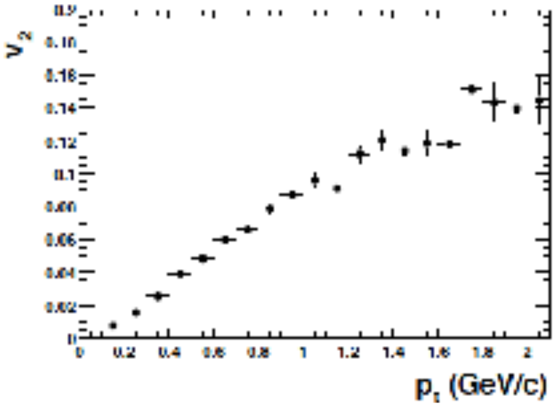
Flow fluctuations

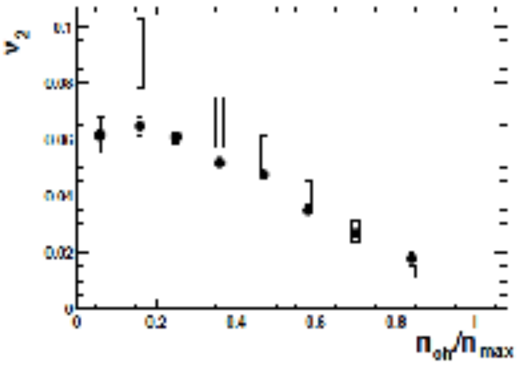
ALICE Collaboration, JHEP 07 (2018) 103



The birth of the sQGP paradigm…

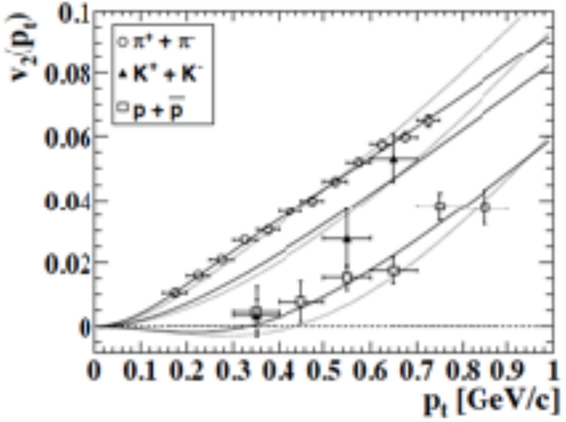
(STAR Collaboration) Phys. Rev. Lett. 86 (2001) 402



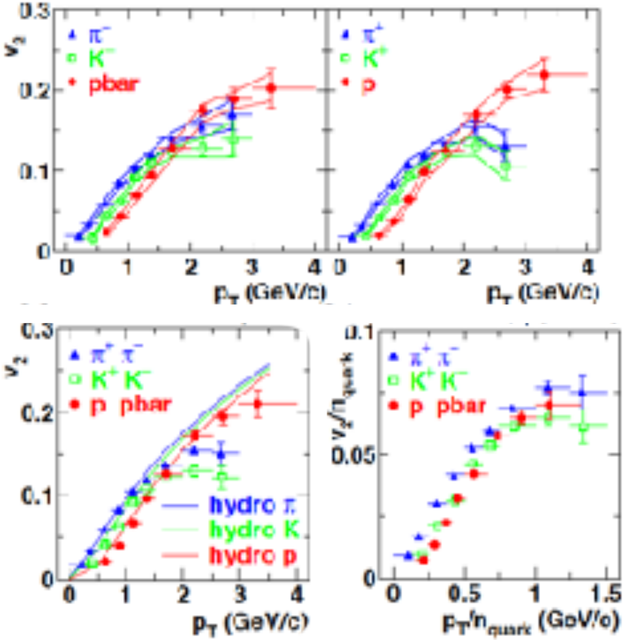


…established by looking at the details

(STAR Collaboration): Phys. Rev. Lett. 87 (2001) 182301

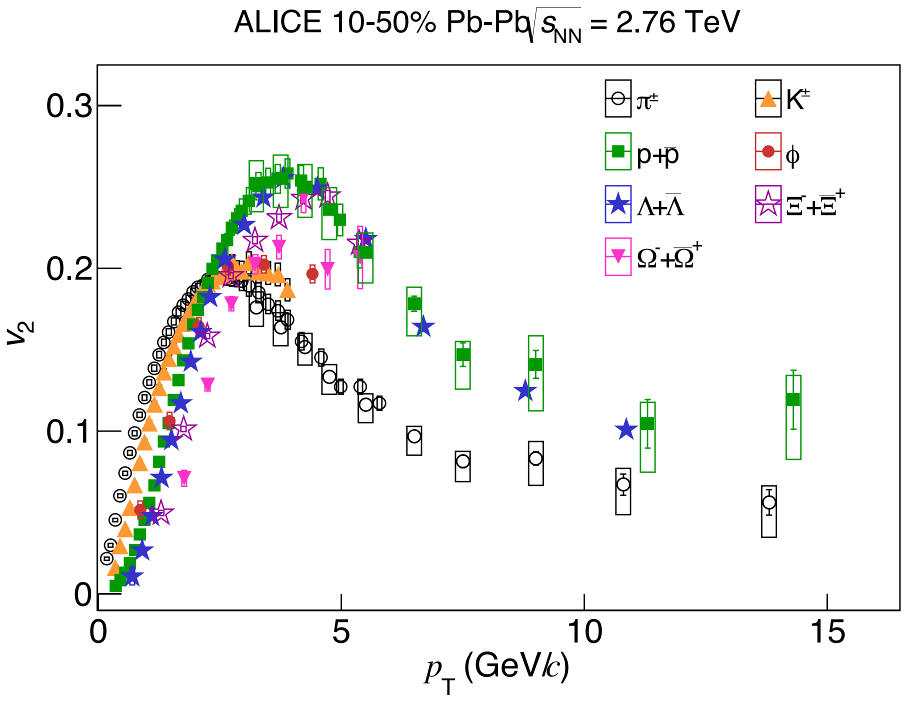


(PHENIX Collaboration): Phys.Rev.Lett.91, 182301,2003



- Mass ordering at low p_T
- Agreement with (ideal) hydrodynamical calculations
- Apparent NCQ scaling at intermediate p_T

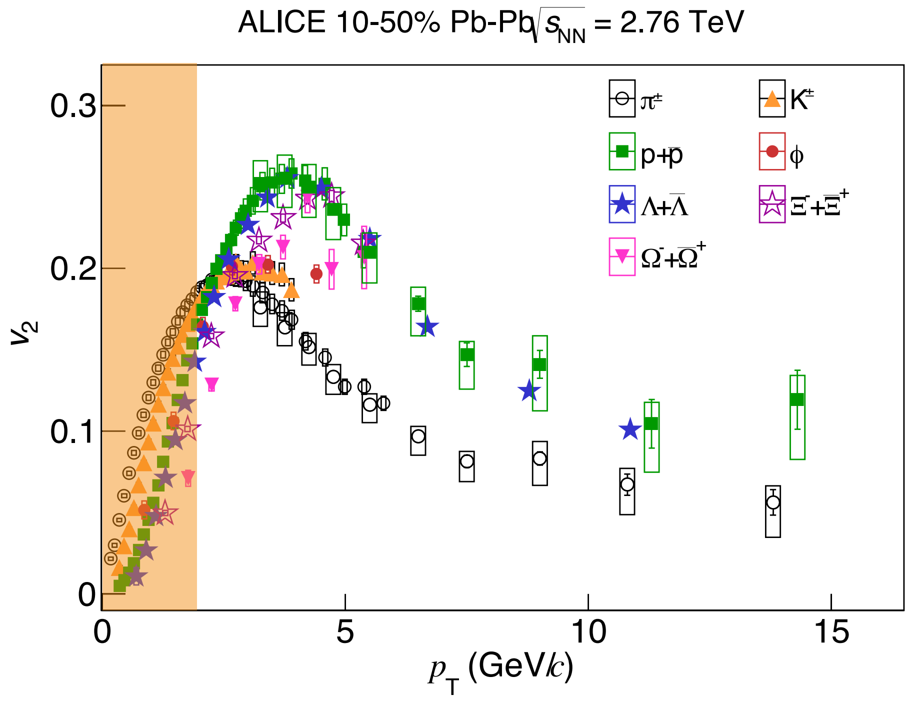
Identified particle v_2 @ LHC



(ALICE), JHEP 06 (2015) 190

(ALICE), Physics Letters B 719 (2013) 18

Identified particle v_2 @ LHC: low p_T

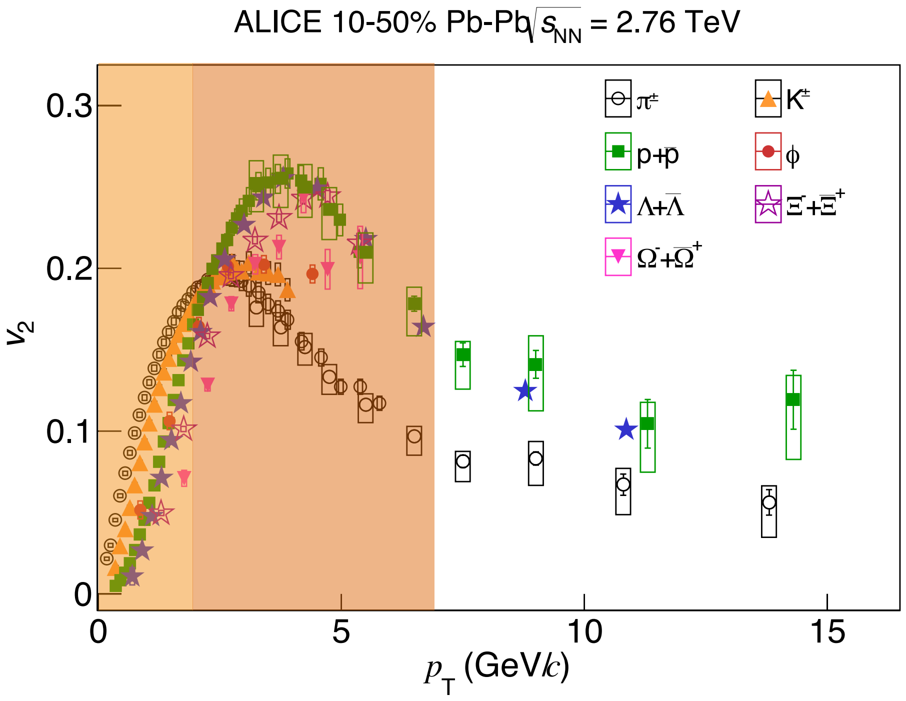


Bulk of particle production: described in terms of hydrodynamics

(ALICE), JHEP 06 (2015) 190

(ALICE), Physics Letters B 719 (2013) 18

Identified particle v_2 @ LHC: intermediate p_T

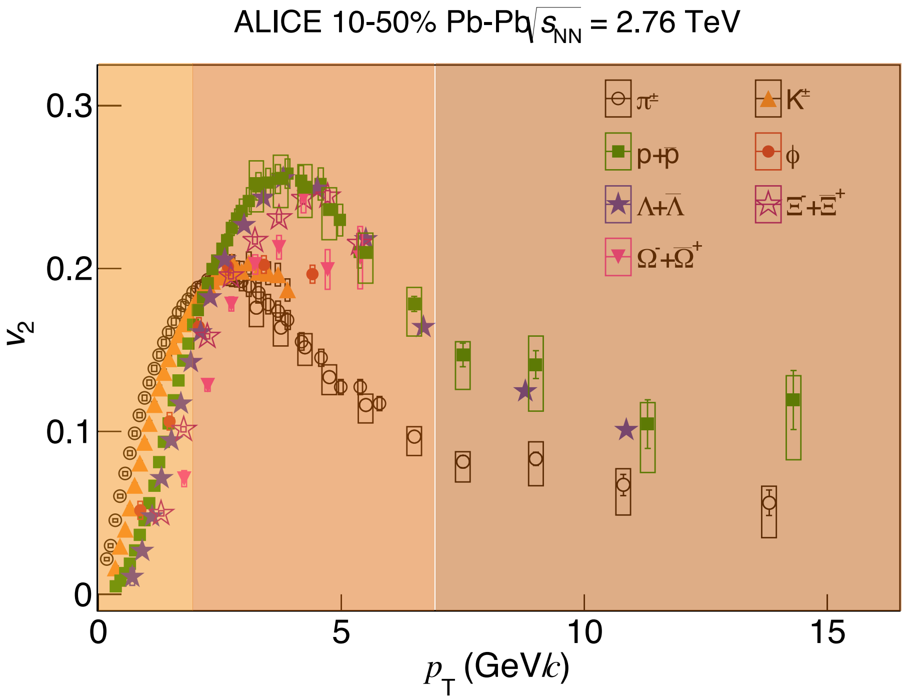


Particle production through coalescence? Evidence of partonic flow?

(ALICE), JHEP 06 (2015) 190

(ALICE), Physics Letters B 719 (2013) 18

Identified particle v_2 @ LHC: high p_T

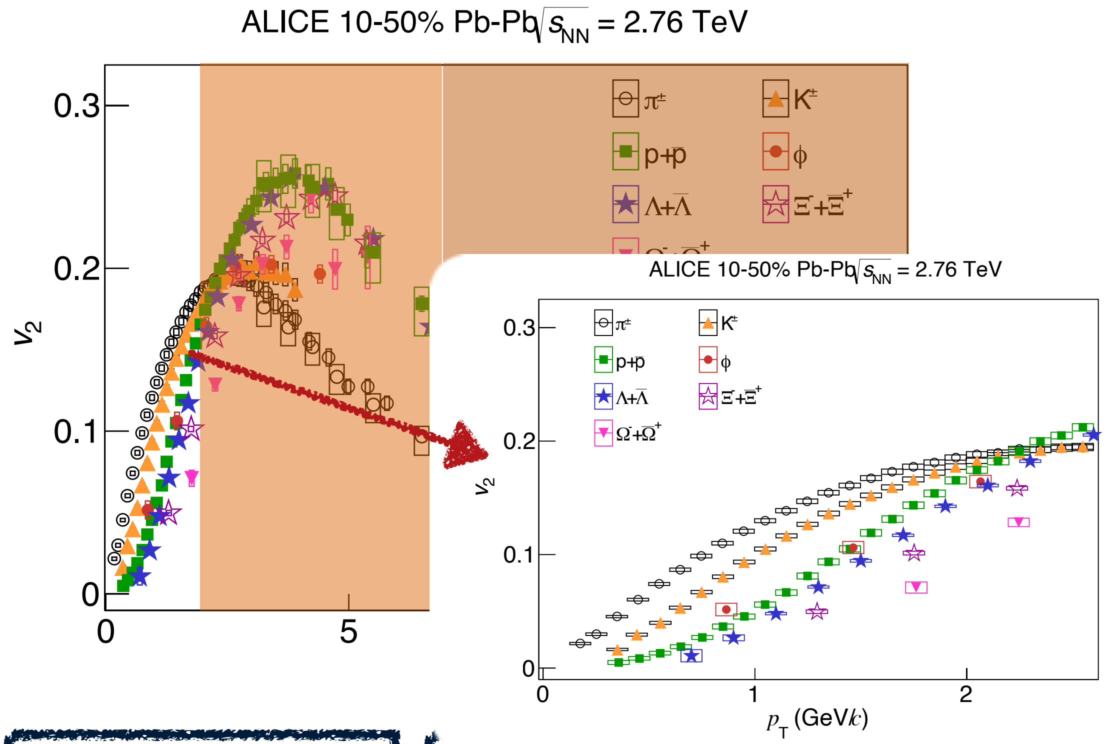


Parton fragmentation: path length dependence of energy loss

(ALICE), JHEP 06 (2015) 190

(ALICE), Physics Letters B 719 (2013) 18

Identified particle v_2 @ LHC: low p_T

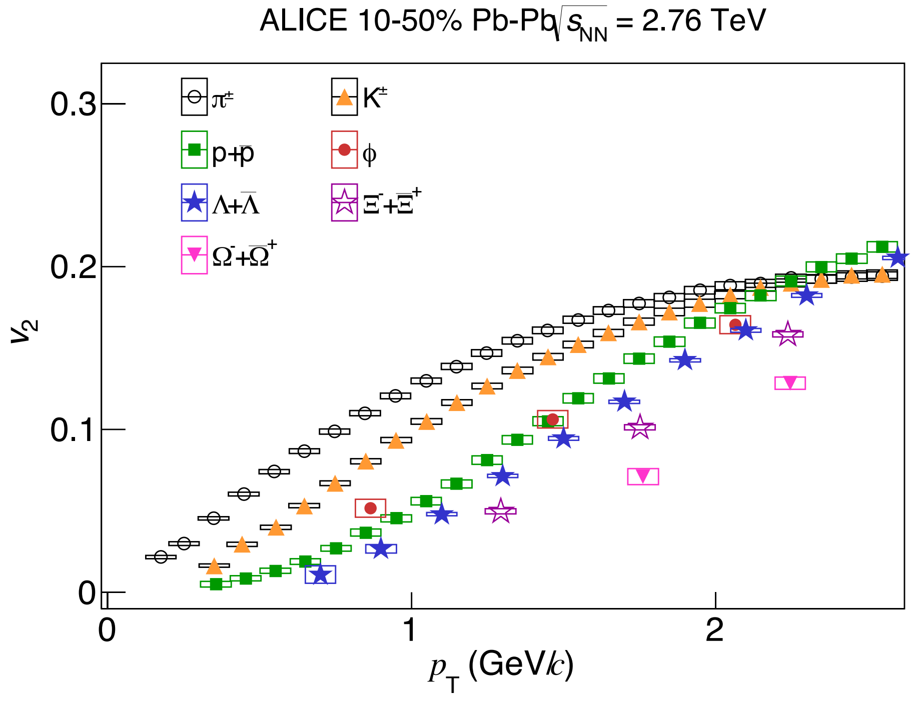


Bulk of particle production: described in terms of hydrodynamics

(ALICE), JHEP 06 (2015) 190

(ALICE), Physics Letters B 719 (2013) 18

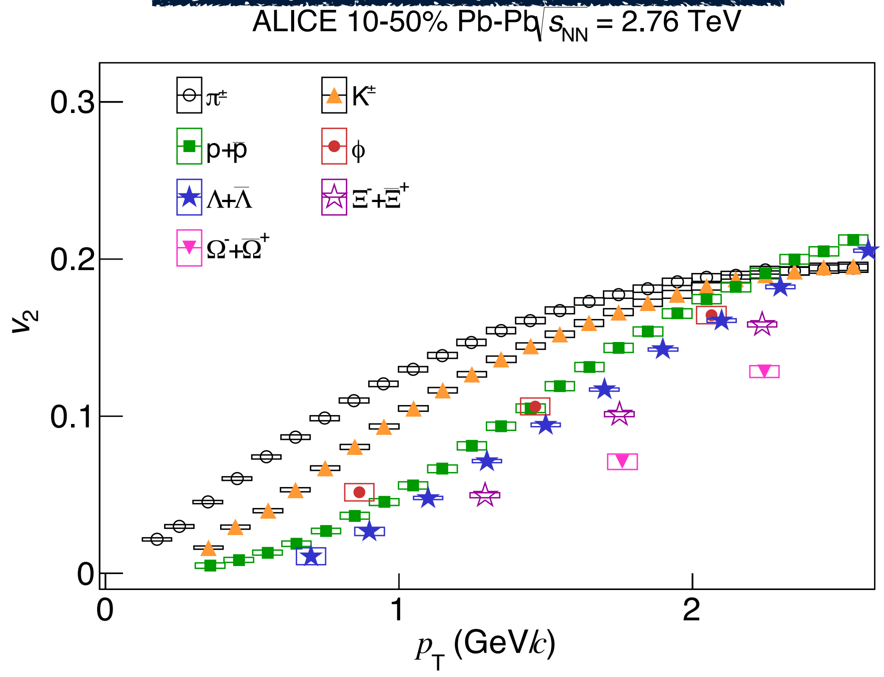
The three momentum scales: low p_T



Low p_T: mass ordering ➜ elliptic/radial flow interplay

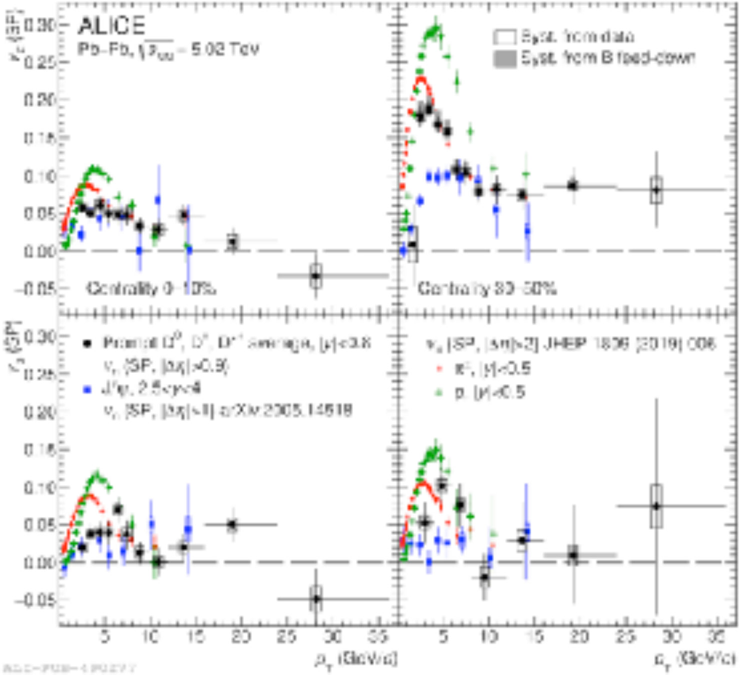
Mass ordering

ALICE Collaboration, JHEP 06 (2015) 190



ALICE Collaboration, PLB 813 (2021) 136054

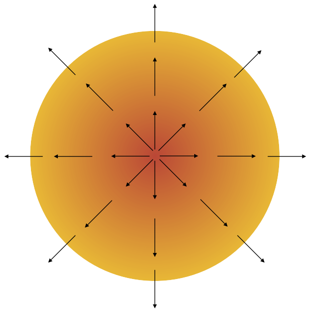
“Respected” also by heavy flavour!

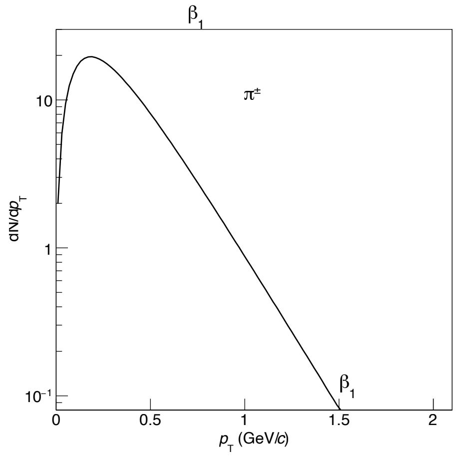


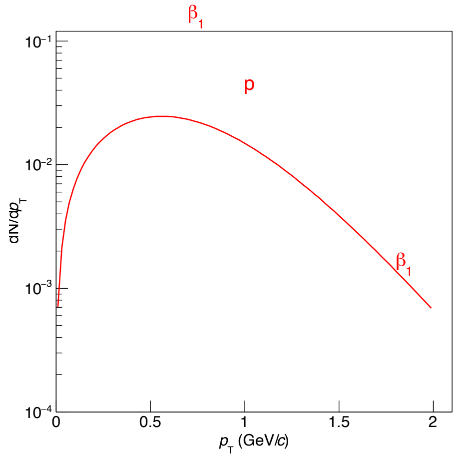
Low p_T: Radial flow embedded in an azimuthally asymmetric environment

Mass ordering

Toy model



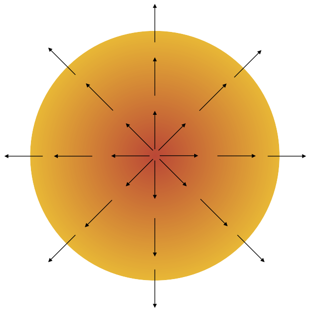


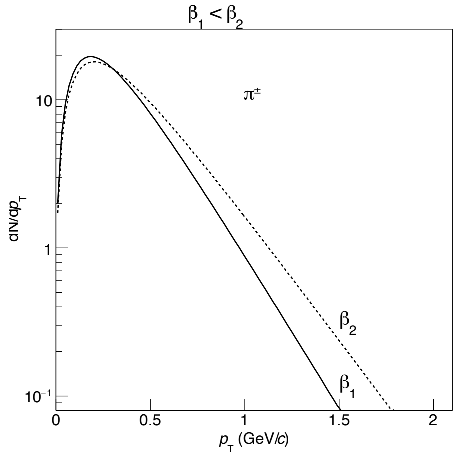


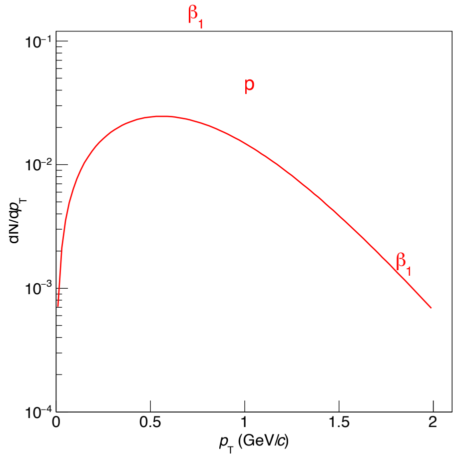
- Radial flow pushes particles to higher p_T → depletion at lower p_T
  - heavier particles "feel" more the boost → the higher the mass the larger the low p_T depletion

Mass ordering

Toy model



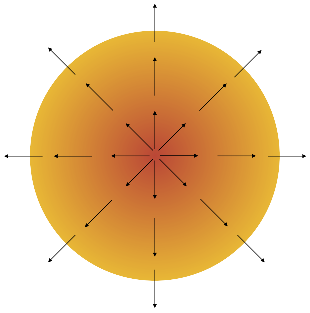


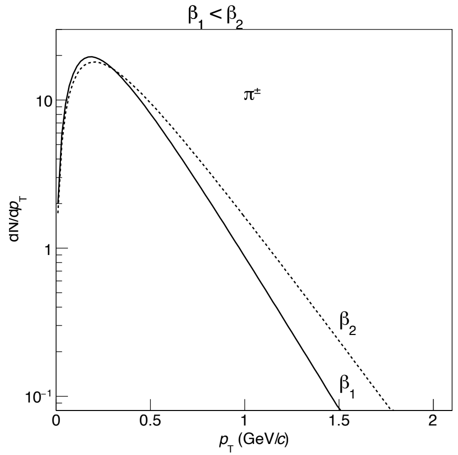


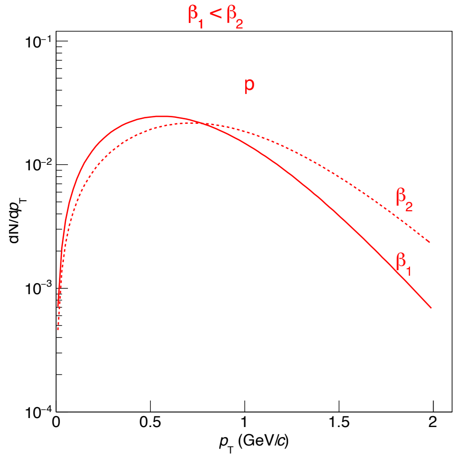
- Radial flow pushes particles to higher p_T ⟶ depletion at lower p_T
  - heavier particles "feel" more the boost ⟶ the higher the mass the larger the low p_T depletion

Mass ordering

Toy model



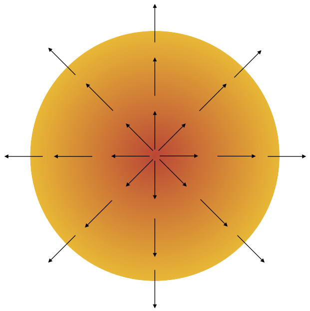


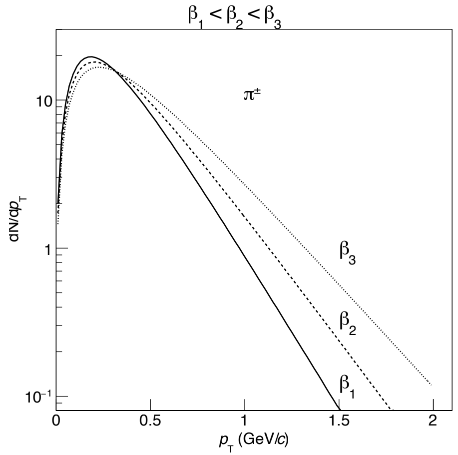


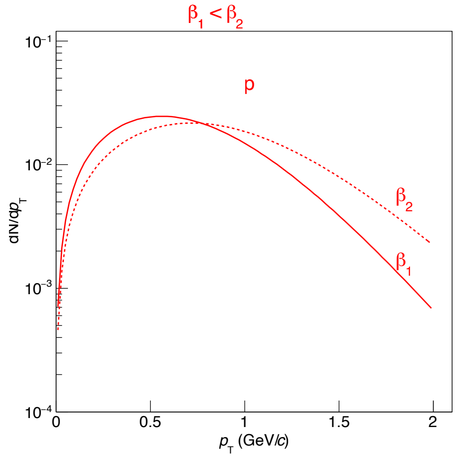
- Radial flow pushes particles to higher p_T → depletion at lower p_T
  - heavier particles "feel" more the boost → the higher the mass the larger the low p_T depletion

Mass ordering

Toy model

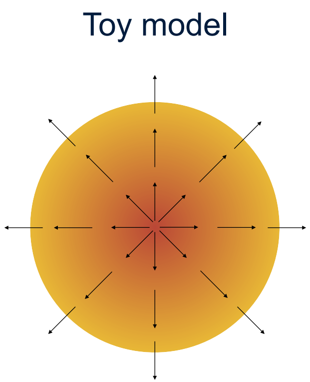


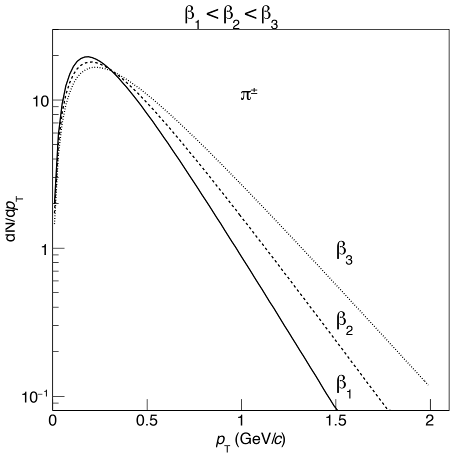


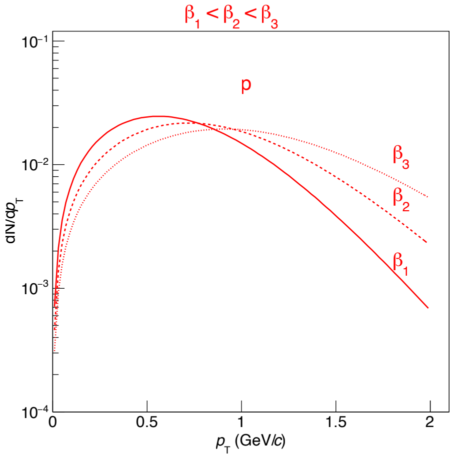


- Radial flow pushes particles to higher p_T → depletion at lower p_T
  - heavier particles "feel" more the boost → the higher the mass the larger the low p_T depletion

Mass ordering

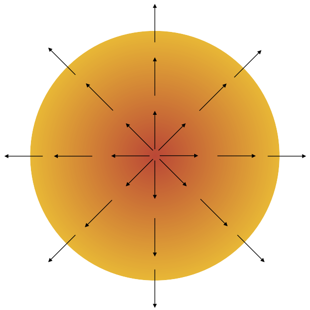


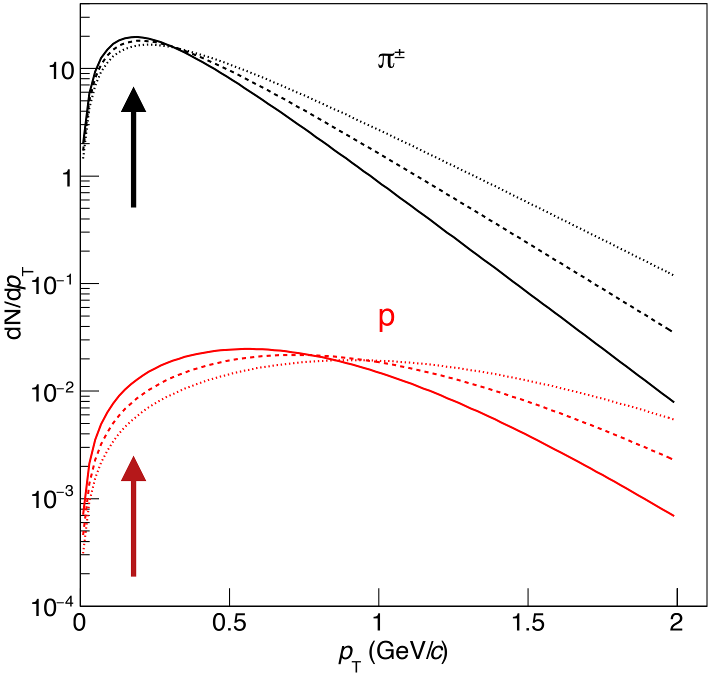




- Radial flow pushes particles to higher p_T ⟶ depletion at lower p_T
  - heavier particles "feel" more the boost ⟶ the higher the mass the larger the low p_T depletion

Mass ordering

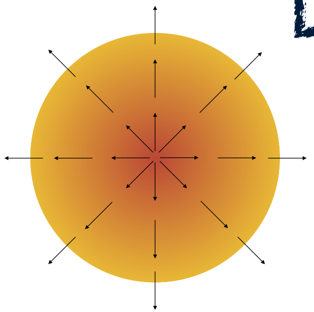




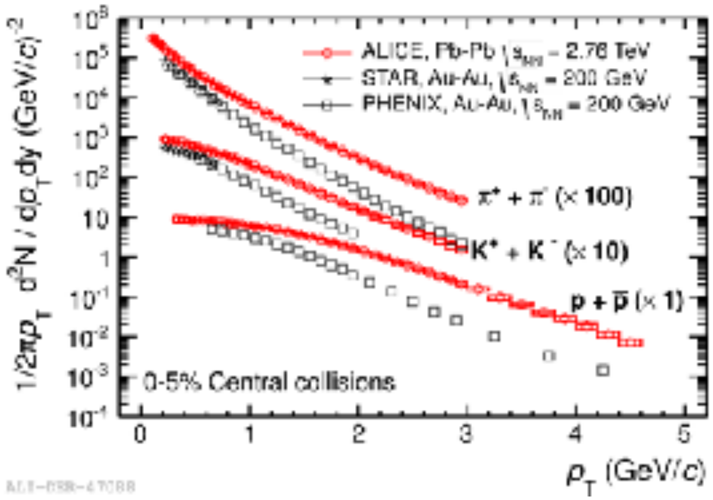
- Radial flow pushes particles to higher p_T ➞ depletion at lower p_T
  - heavier particles "feel" more the boost ➞ the higher the mass the larger the low p_T depletion

Mass ordering

Toy model



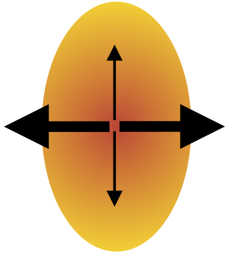
(ALICE Collaboration), Phys. Rev. **C88**, (2013) 044910



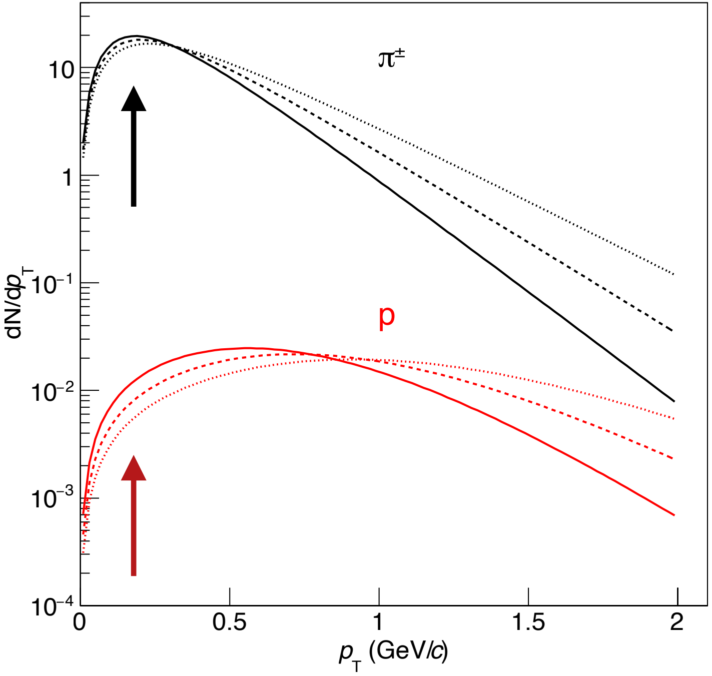
- Radial flow pushes particles to higher p_T → depletion at lower p_T
  - heavier particles "feel" more the boost → the higher the mass the larger the low p_T depletion

Mass ordering

Toy model
Azimuthally asymmetric system



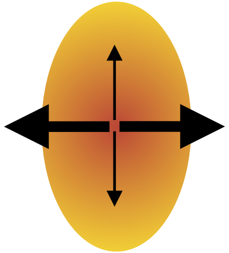
$$v_2 \propto \frac{N_{in} - N_{out}}{N_{in} + N_{out}}$$



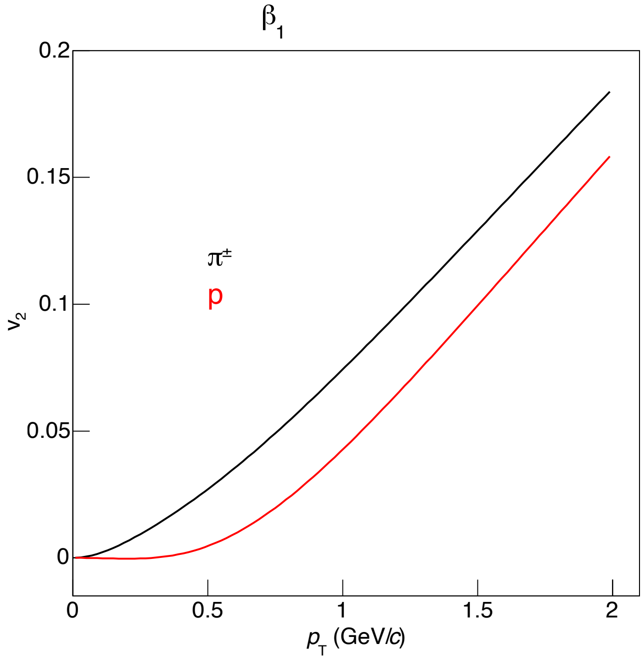
- Larger “push” in-plane than out-of-plane as a function of mass
  - larger low-p_T depletion in-plane than out-of-plane ➞ lower v_2 in a mass dependent way

Mass ordering

Toy model
Azimuthally asymmetric system



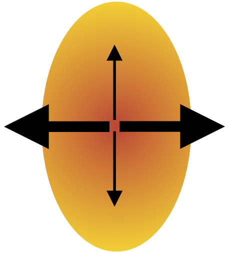
$$v_2 \propto \frac{N_{in} - N_{out}}{N_{in} + N_{out}}$$



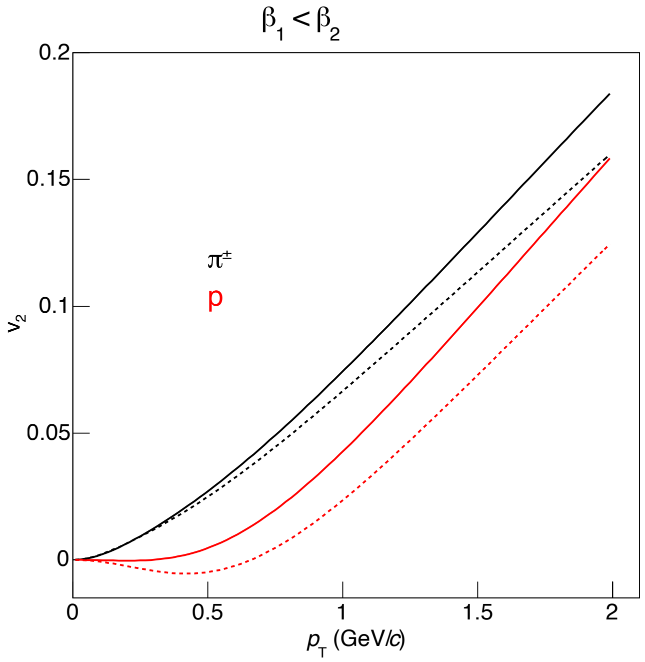
- Larger "push" in-plane than out-of-plane as a function of mass
  - larger low-p_T depletion in-plane than out-of-plane ➞ lower v_2 in a mass dependent way

Mass ordering

Toy model
Azimuthally asymmetric system



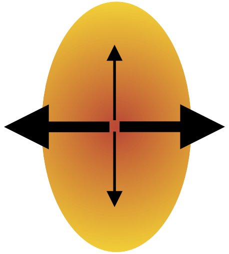
$$v_2 \propto \frac{N_{in} - N_{out}}{N_{in} + N_{out}}$$



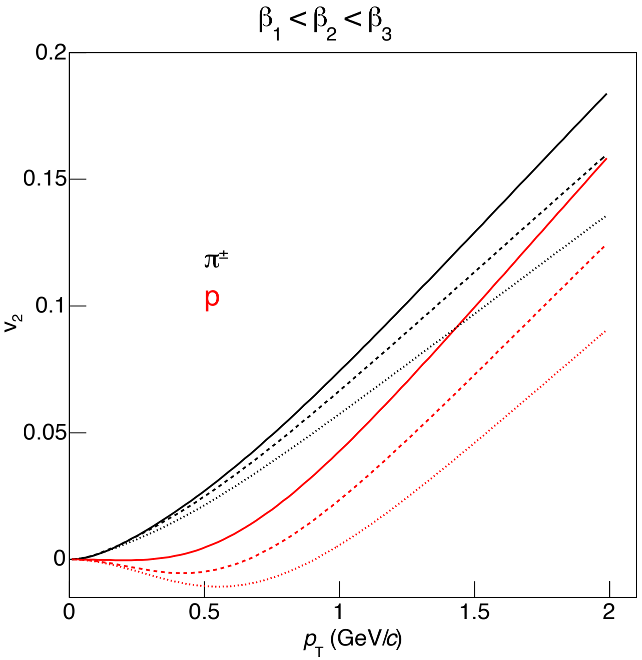
- Larger "push" in-plane than out-of-plane as a function of mass
  - larger low-p_T depletion in-plane than out-of-plane ➞ lower v_2 in a mass dependent way

Mass ordering

Toy model
Azimuthally asymmetric system



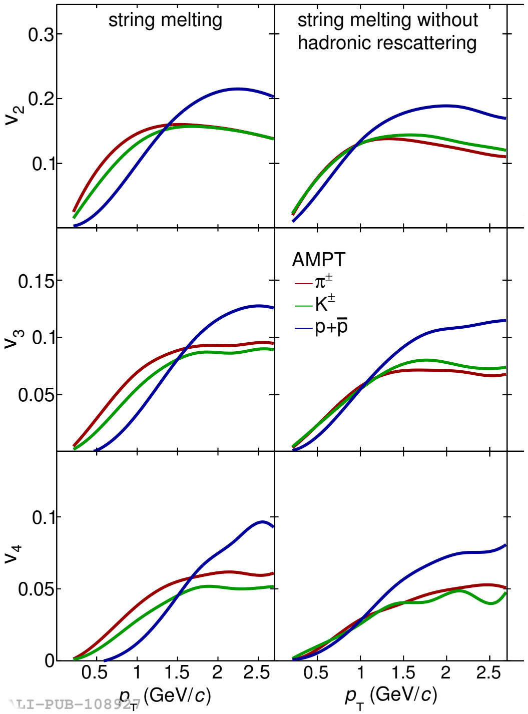
$$v_2 \propto \frac{N_{in} - N_{out}}{N_{in} + N_{out}}$$



- Larger "push" in-plane than out-of-plane as a function of mass
  - larger low-p_T depletion in-plane than out-of-plane ➞ lower v_2 in a mass dependent way

Effect of hadronic rescattering

(ALICE Collaboration), JHEP **09** (2016) 164



Hadronic rescattering has significant contribution to the observed mass ordering

Hydrodynamic description

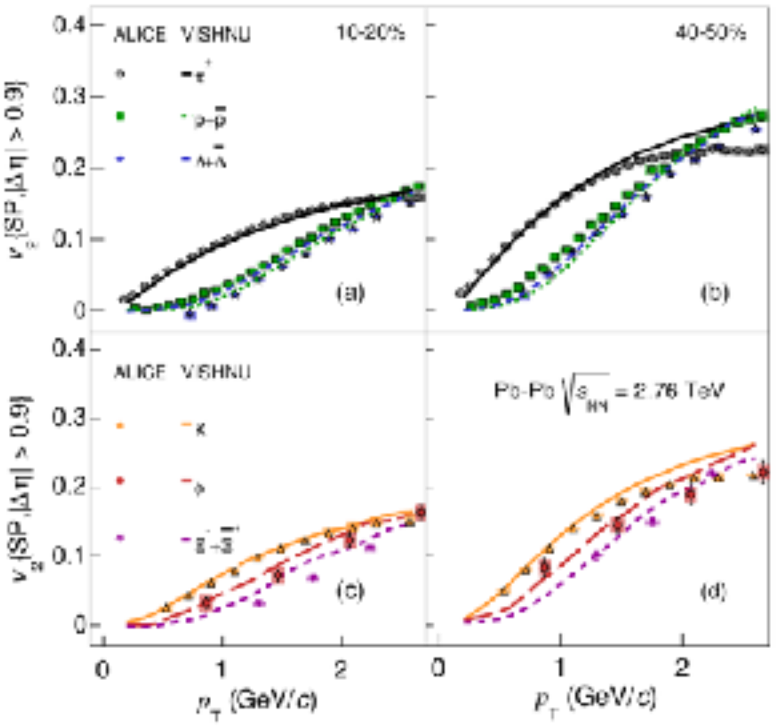
VISHNU

- Couples VISH2+1 to UrQMD
- MC-KLN density profiles
- $\eta/s = 0.16$
- $\tau_0 = 0.9$ fm/c

H. Song, S. A. Bass, U. Heinz, T. Hirano and C. Shen, Phys. Rev. Lett. 106 (2011) 192301 [Erratum-ibid. 109 (2012) 139904] [arXiv:1011.2783 [nucl-th]].

H. Song, S. A. Bass, U. Heinz, T. Hirano and C. Shen, Phys. Rev. C 83 (2011) 054910 [Erratum-ibid. C 86 (2012) 059903] [arXiv:1101.4638 [nucl-th]].

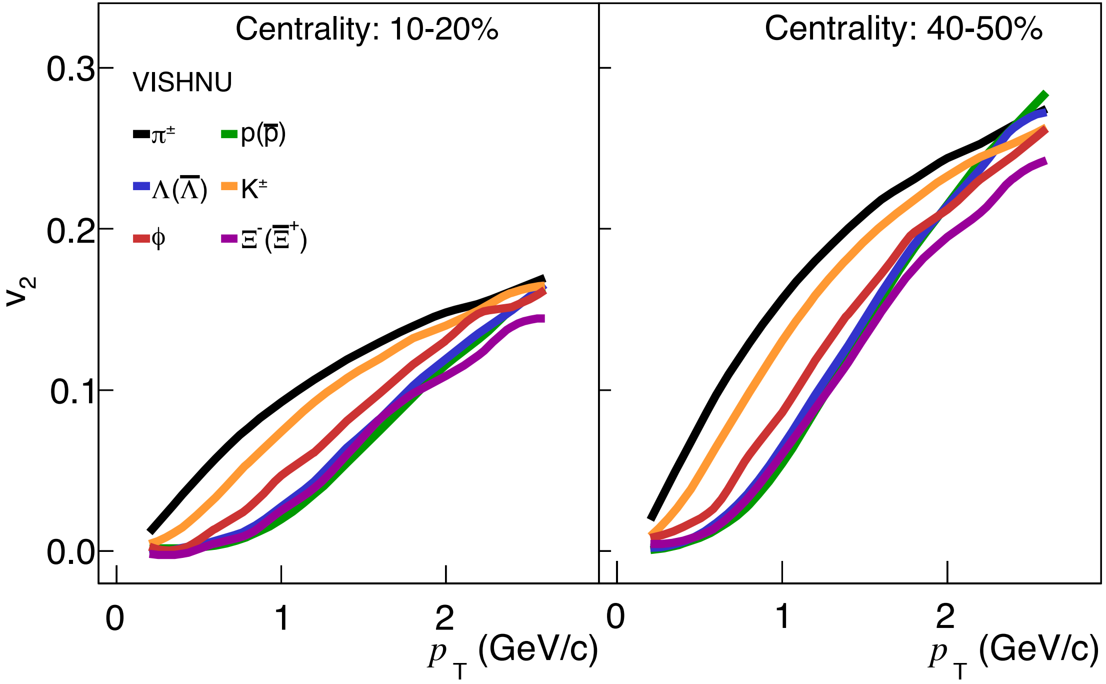
H. Song, S. Bass and U. W. Heinz, arXiv:1311.0157 [nucl-th].



Looking at the details…

- $m_\phi > m_p$
  - mass ordering leads to $v_2^\phi < v_2^p$
  - VISHNU expects that to break

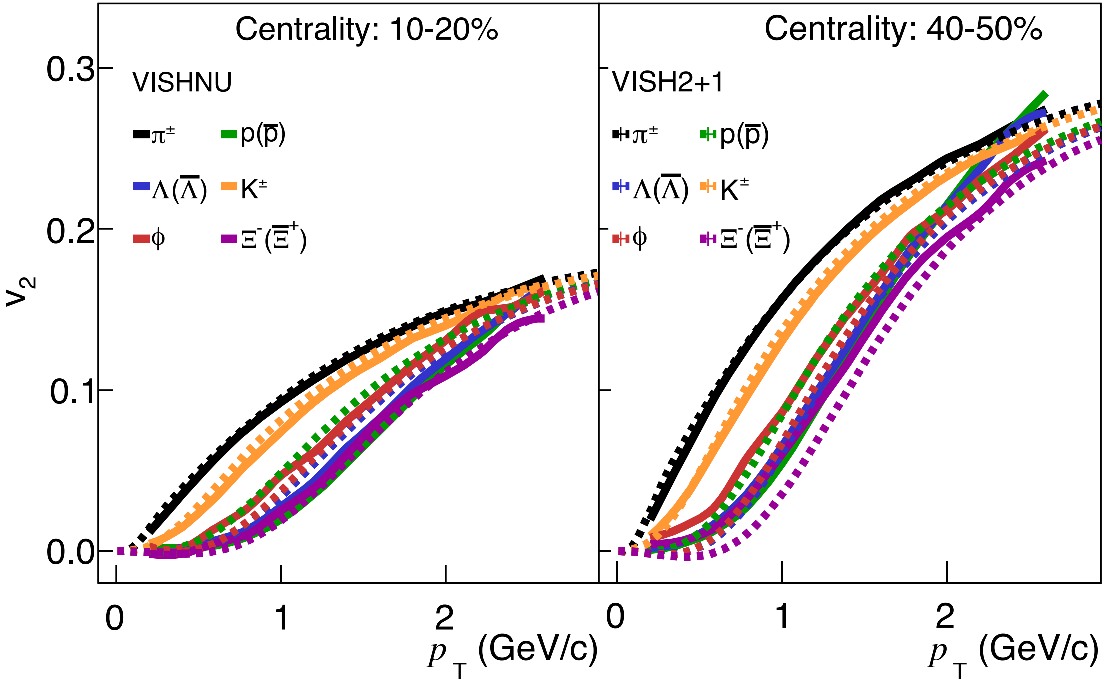
Mass ordering not preserved!!!



The effect of the hadronic phase

VISH2+1

- 2+1 hydro without hadronic cascade
- Glauber density profiles
- $\eta/s = 0.08$
- $\tau_0 = 0.6$ fm/c



H. Song and U. W. Heinz, Phys. Lett. B 658 (2008) 279 [arXiv:0709.0742 [nucl-th]].

H. Song and U. W. Heinz, Phys. Rev. C 77 (2008) 064901 [arXiv:0712.3715 [nucl-th]].

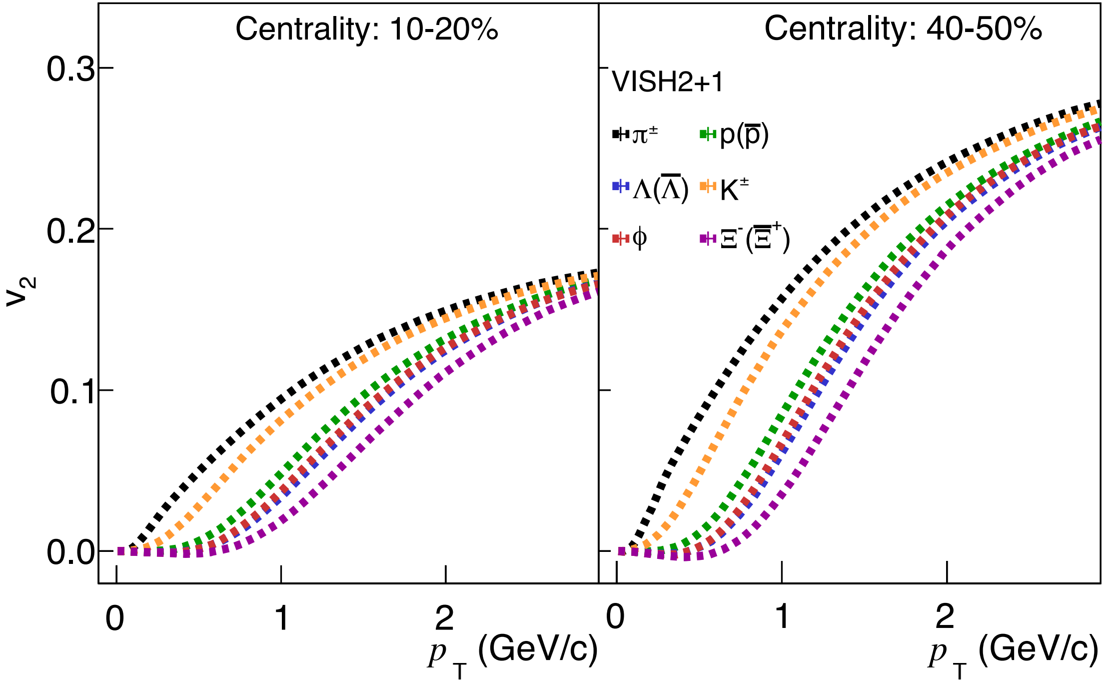
H. Song and U. W. Heinz, Phys. Rev. C 78 (2008) 024902 [arXiv:0805.1756 [nucl-th]].

The effect of the hadronic phase

VISH2+1

- 2+1 hydro without hadronic cascade
- Glauber density profiles
- $\eta/s = 0.08$
- $\tau_0 = 0.6$ fm/c

Mass ordering preserved!!!



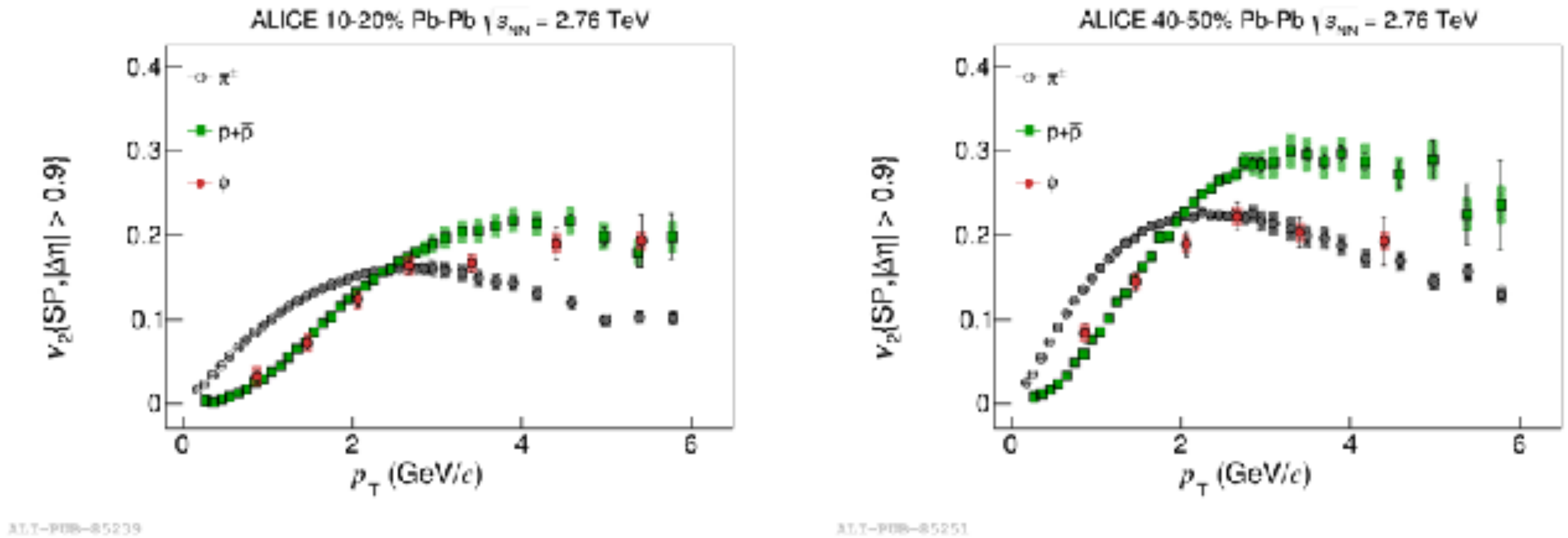
H. Song and U. W. Heinz, Phys. Lett. B 658 (2008) 279 [arXiv:0709.0742 [nucl-th]].

H. Song and U. W. Heinz, Phys. Rev. C 77 (2008) 064901 [arXiv:0712.3715 [nucl-th]].

H. Song and U. W. Heinz, Phys. Rev. C 78 (2008) 024902 [arXiv:0805.1756 [nucl-th]].

The special role of the ϕ-meson

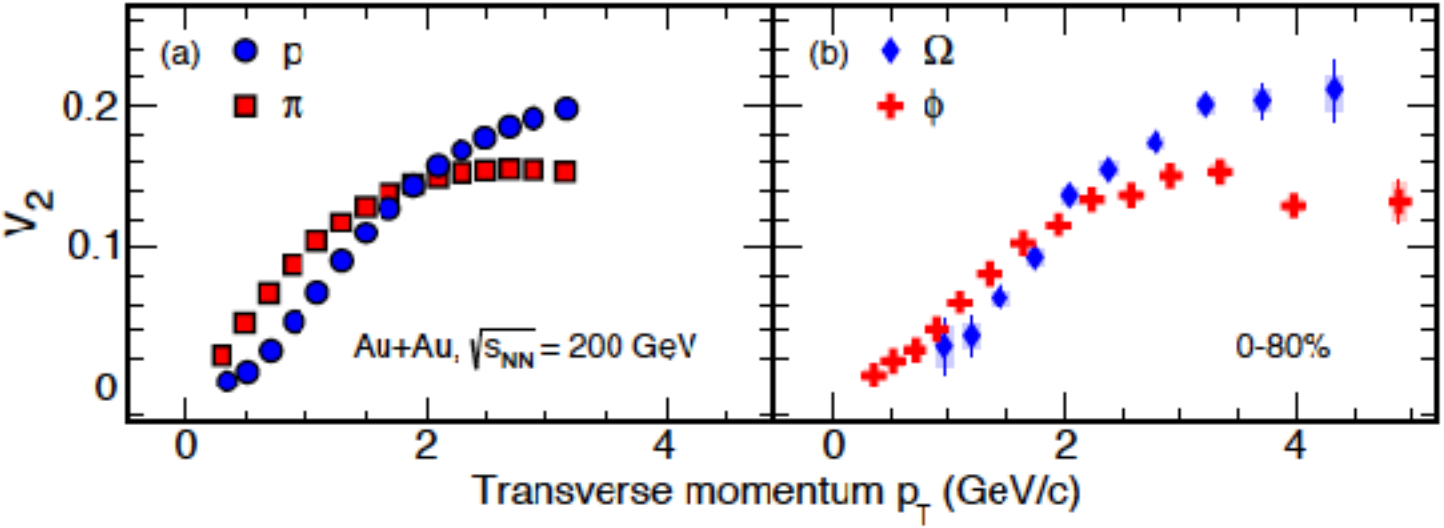
B. Abelev *et al*. (ALICE Collaboration), JHEP 06 (2015) 190



First bins may hint at different ordering…still inconclusive

Mass ordering @ RHIC

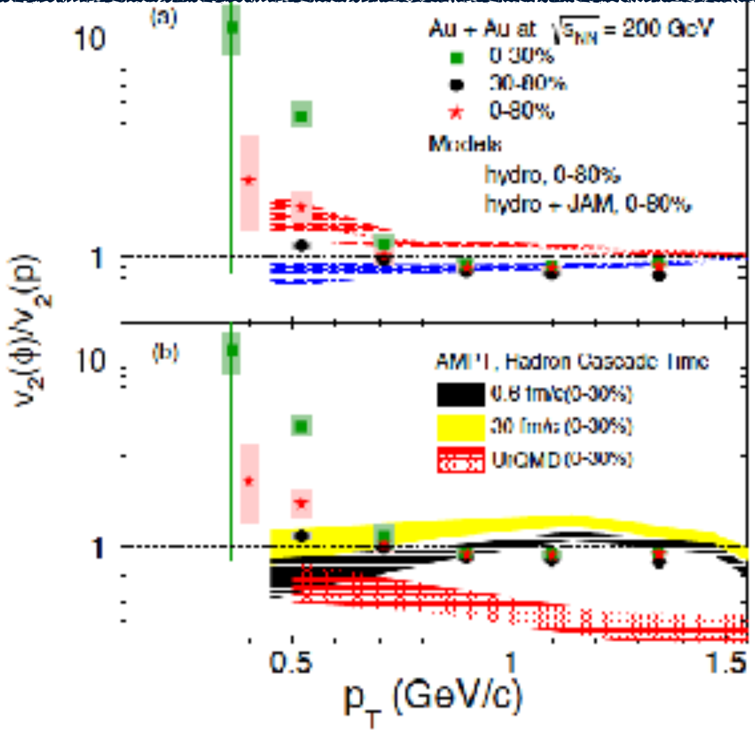
L. Adamczyk *et al*. (STAR Collaboration), Phys. Rev. Lett. 116, (2016) 062301



Mass ordering preserved @ RHIC?

Mass ordering violation @ RHIC

L. Adamczyk *et al*. (STAR Collaboration), Phys. Rev. Lett. 116, (2016) 062301



Violation of mass ordering: hadronic rescattering effect

T. Hirano *et al.*, Phys.Rev. C77 (2008) 044909

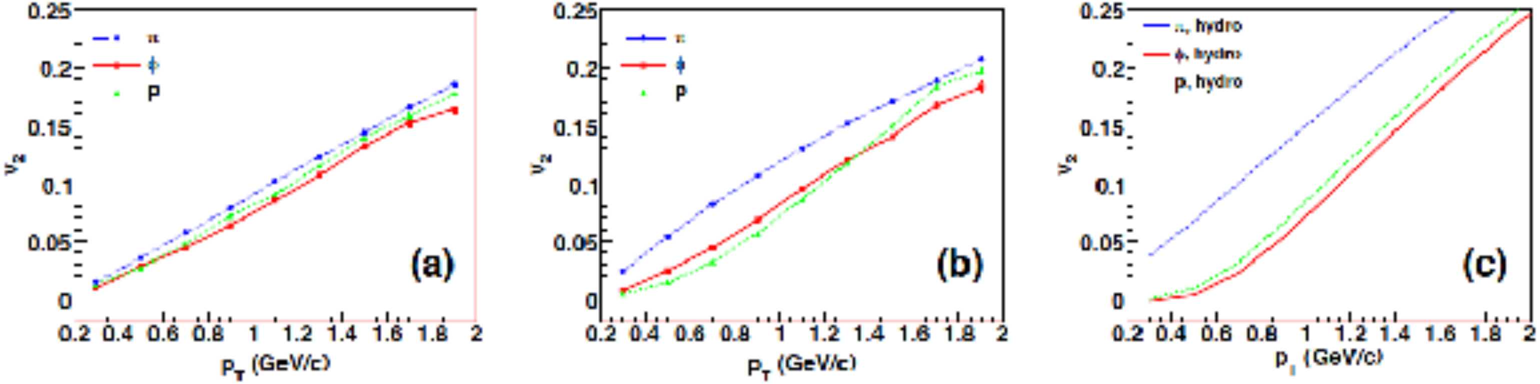
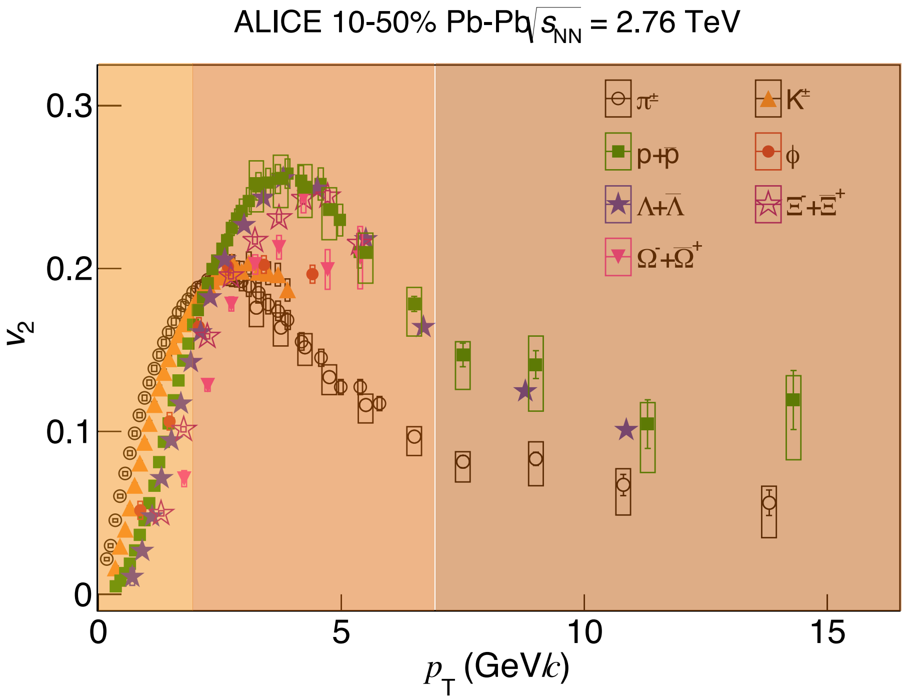


FIG. 9: (Color online) Transverse momentum dependence of the elliptic flow parameters for pions (dotted blue), protons (dashed green), and ϕ mesons (solid red), for Au+Au collisions at $b = 7.2$ fm. (a) Before hadronic rescattering. (b) After hadronic rescattering. (c) Ideal hydrodynamics with $T_{th} = 100$ MeV. The results for pions and protons are the same as shown in Fig. 5.

Identified particle v_2 @ LHC: high p_T

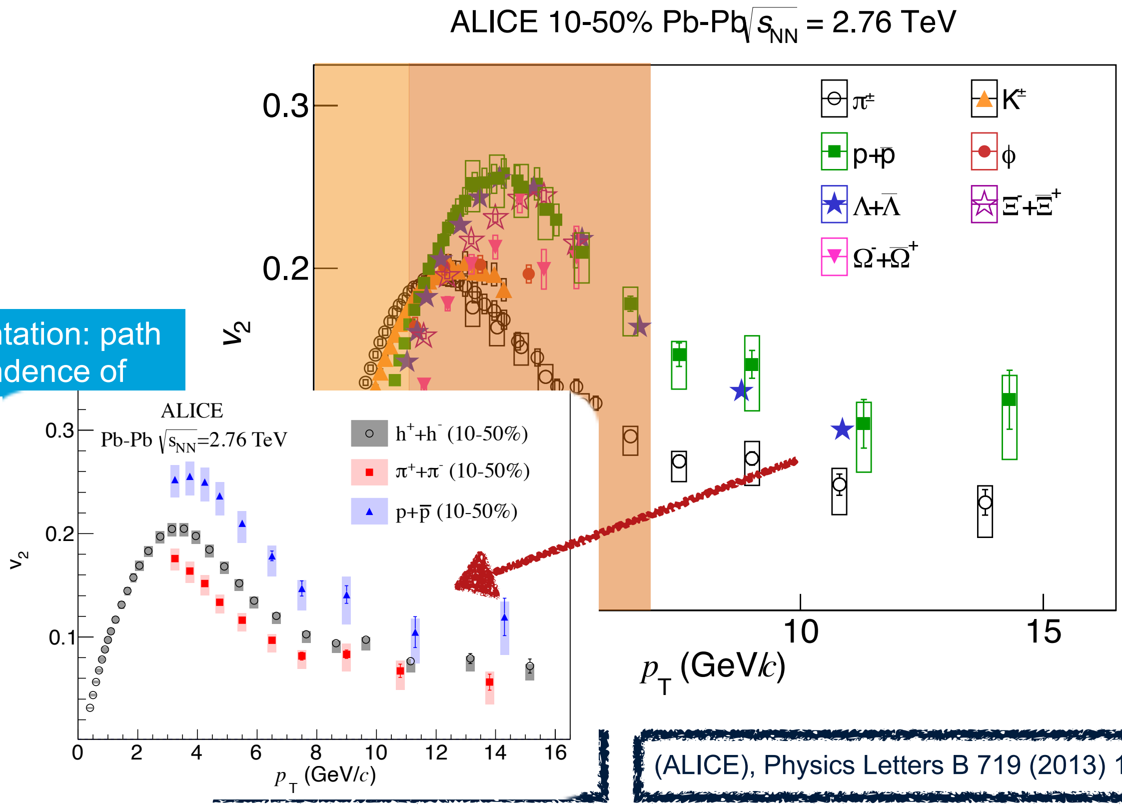


Parton fragmentation: path length dependence of energy loss

(ALICE), JHEP 06 (2015) 190

(ALICE), Physics Letters B 719 (2013) 18

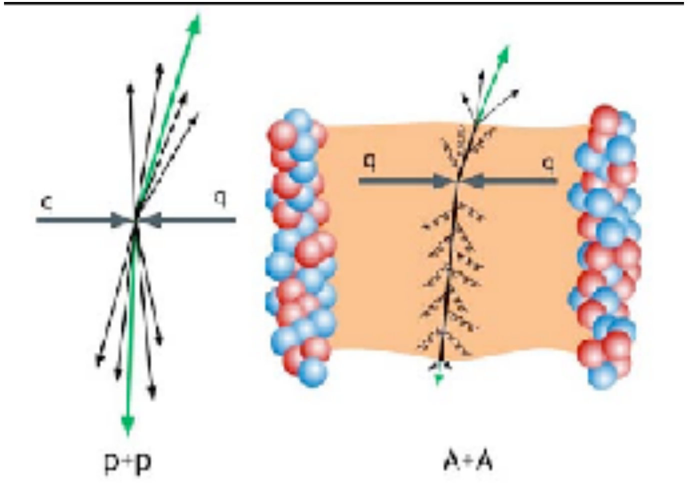
Identified particle v_2 @ LHC: high p_T

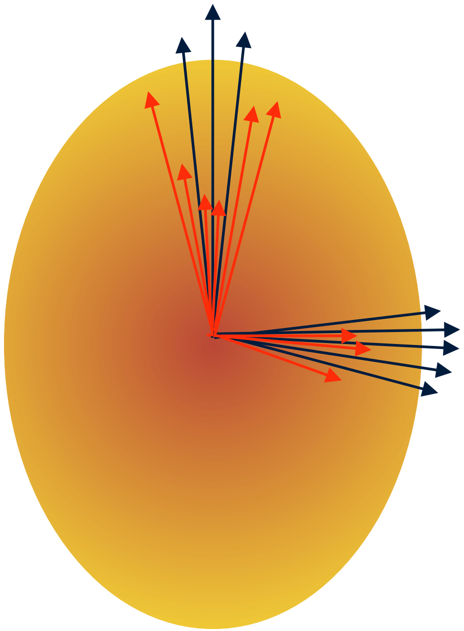


Parton fragmentation: path length dependence of energy

(ALICE), Physics Letters B 719 (2013) 18

The three momentum scales: high p_T

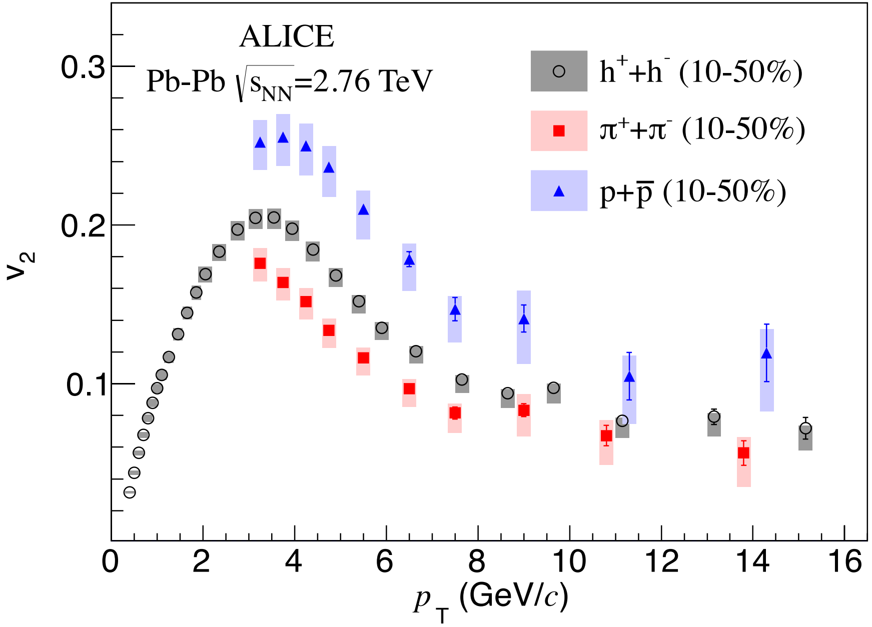




- Probing the path length dependence of energy loss
  - particles flying in-plane have to travel through less (more) medium
  - expect to see an azimuthal dependence of jets and high p_T particles observed at low p_T at RHIC energies

The three momentum scales: high p_T

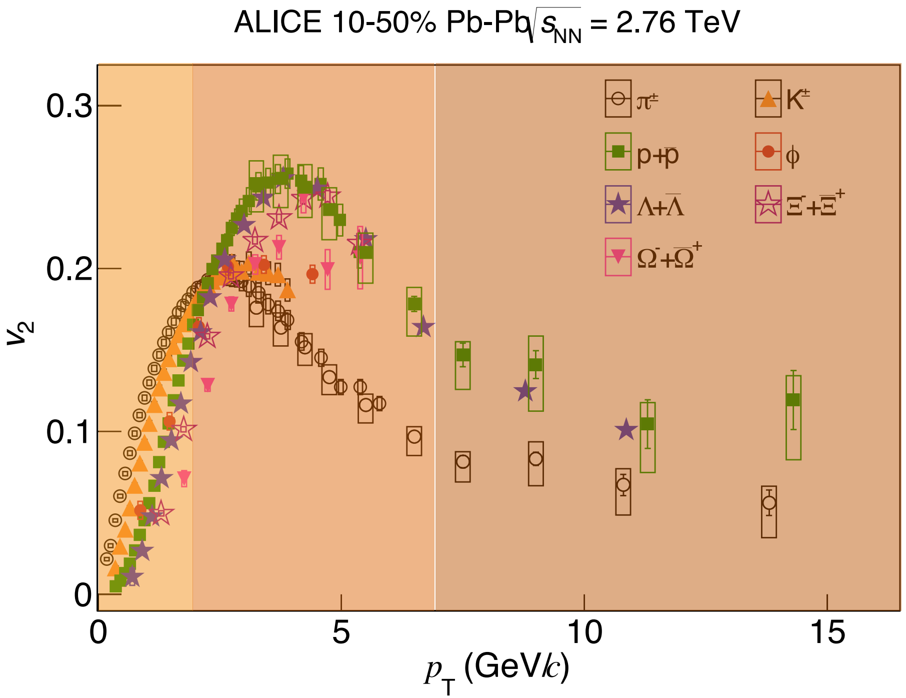
B. Abelev *et al*. (ALICE Collaboration), Phys. Lett. **B719**, (2013) 18



Significant v_2 for all particle species at high p_T with no significant particle species dependence for p_T > 10 GeV/c

Identified particle v_2 @ LHC: intermediate p_T

Particle production through coalescence? Evidence of partonic flow?

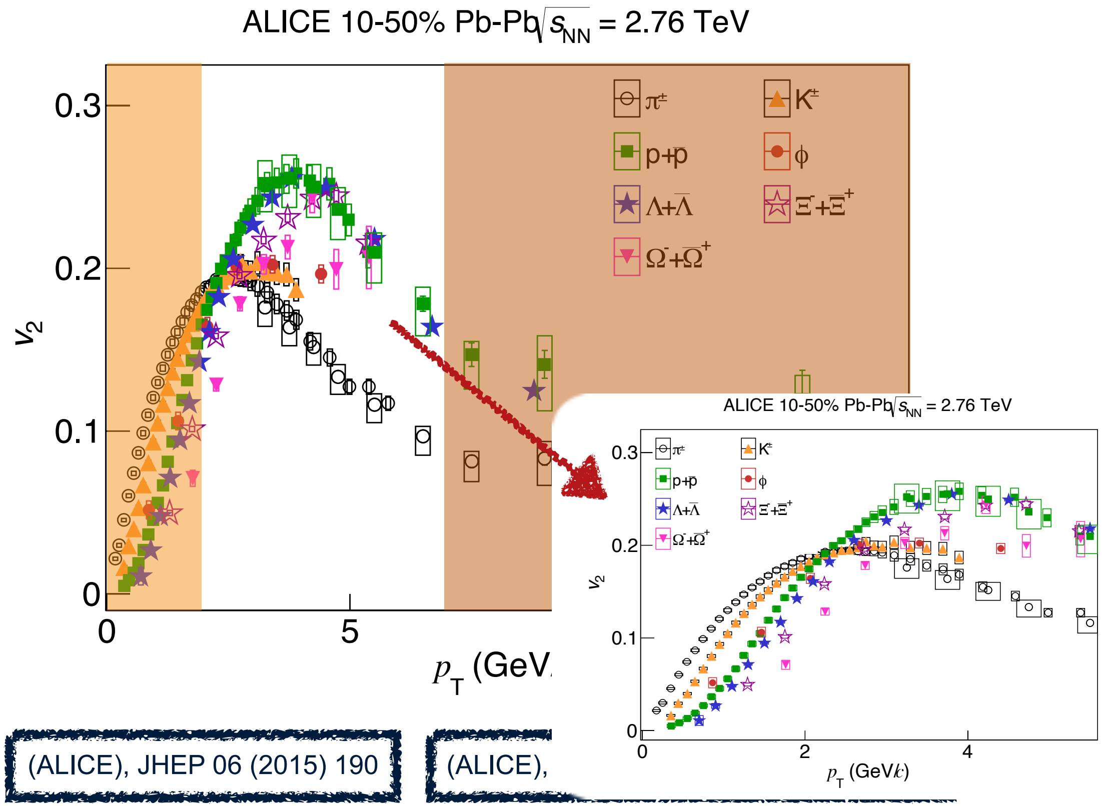


(ALICE), JHEP 06 (2015) 190

(ALICE), Physics Letters B 719 (2013) 18

Identified particle v_2 @ LHC: intermediate p_T

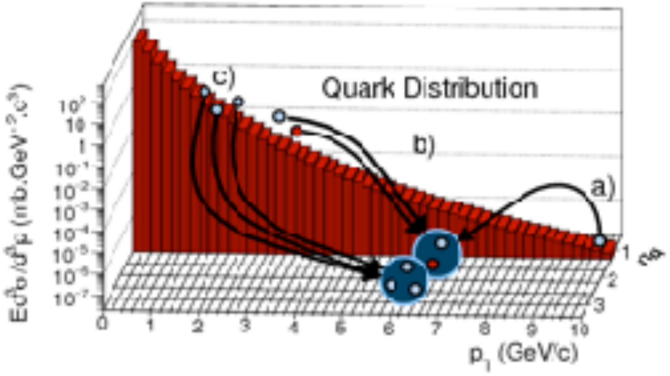
Particle production through coalescence? Evidence of partonic flow?



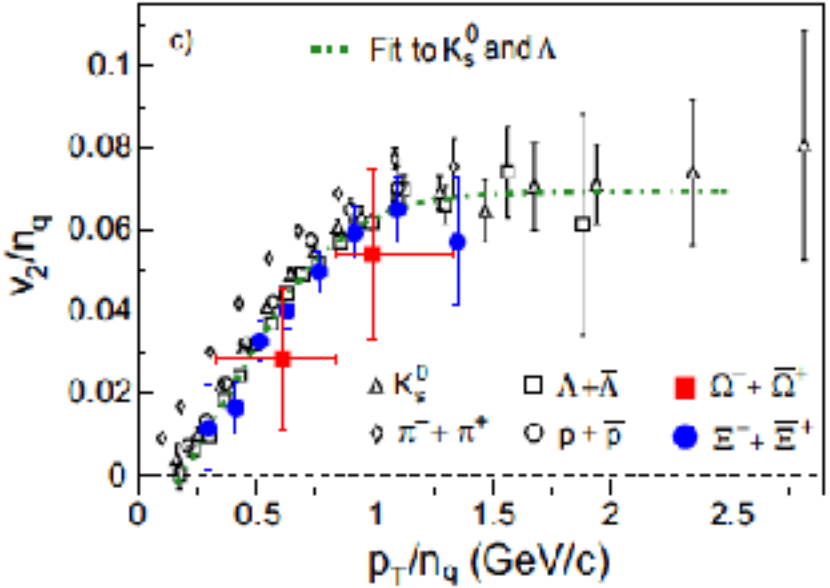
(ALICE), JHEP 06 (2015) 190

(ALICE),

The three momentum scales: intermediate p_T

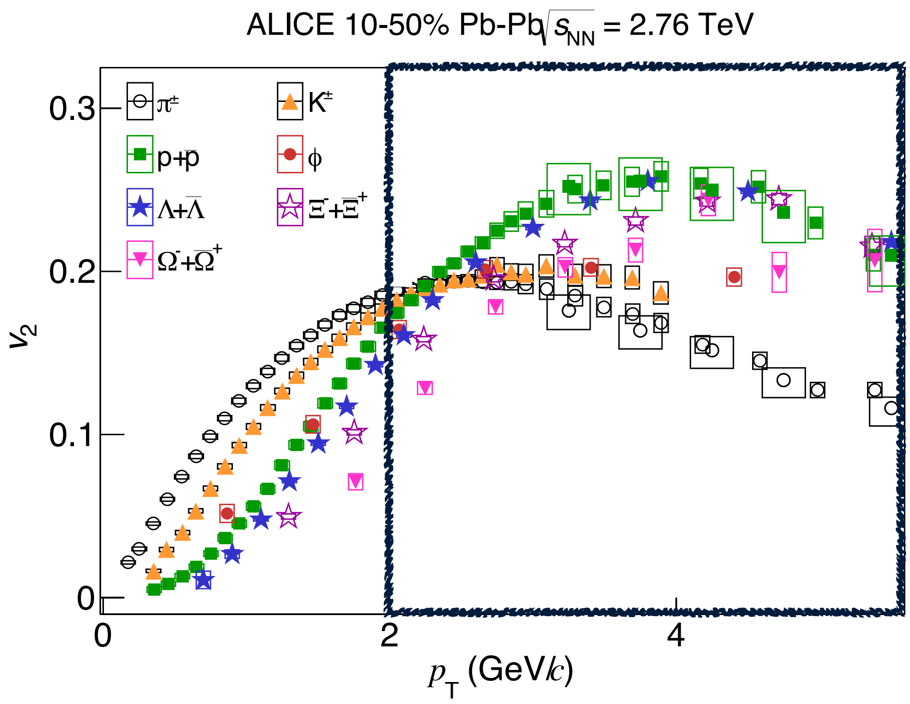


J. Adams *et al.*, (STAR Collaboration), Nucl.Phys. **A757** (2005) 102
K. Adcox *et al.*, (PHENIX Collaboration), Nucl. Phys. **A757**, (2005) 184



- Number of constituent quark (NCQ) scaling holding with good accuracy at RHIC
  - quarks coalesce forming hadrons?
  - NCQ scaling was considered as "evidence" of partonic degrees of freedom ordering observed at low p_T at RHIC energies

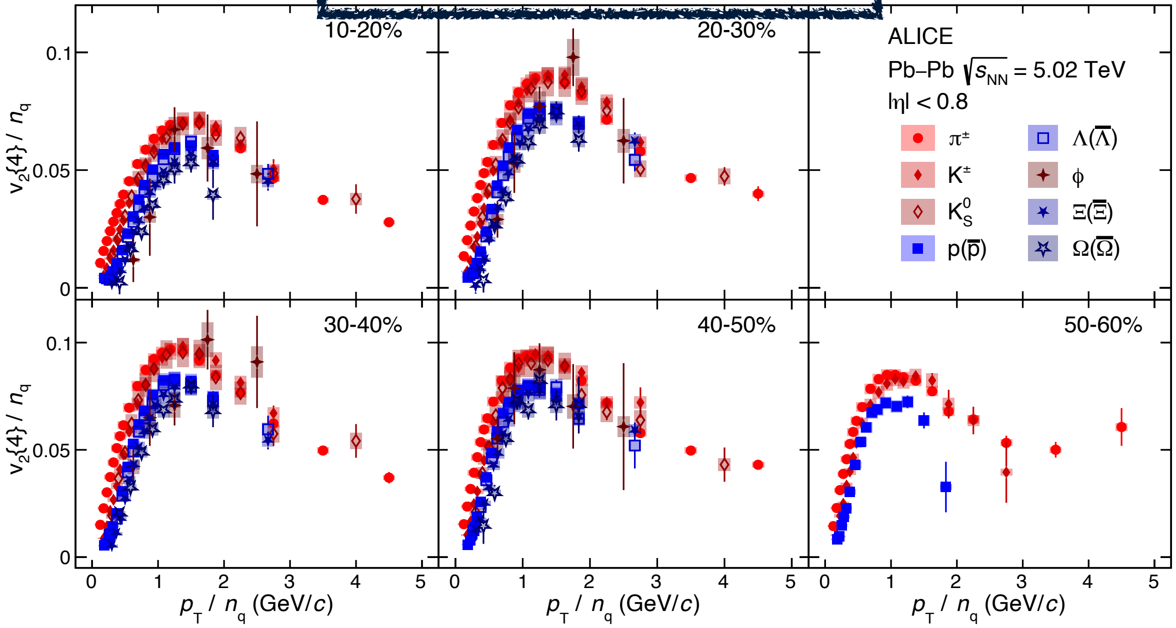
NCQ scaling “at work”



Particle type grouping

*Do not confuse coalescence with hydrodynamics!!!

(ALICE Collaboration), JHEP05 (2023) 243

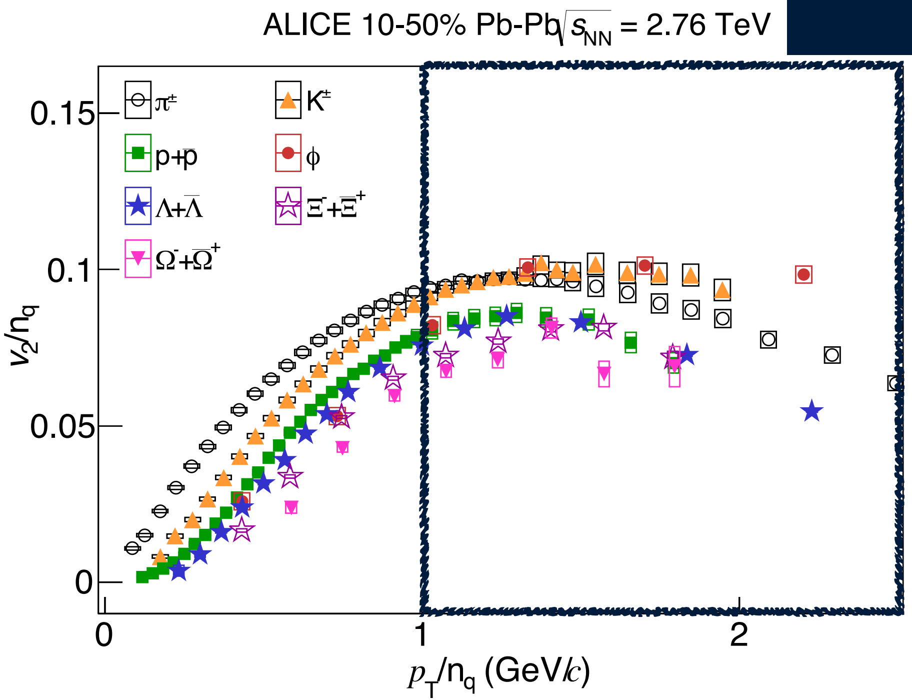


Approximate NCQ scaling → indicative of coalescence as dominant particle production mechanism*

NCQ scaling “at work”

*Scaling holds or breaks down at a similar level at the LHC and at RHIC

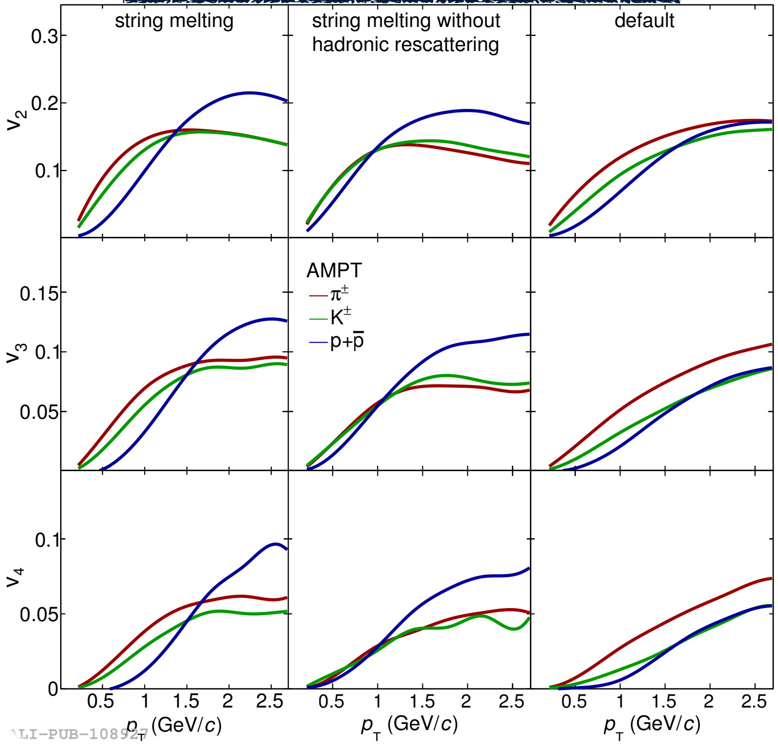
- Theory was already based on approximations → need for refinement
  - how does hadronic rescattering affect the scaling?
  - What’s the spillover effect from the fragmentation/ hydro regions?

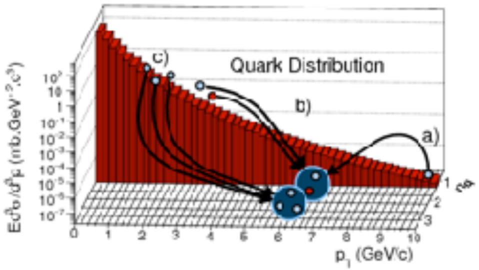


Scaling works at an approximate level*

Particle type grouping

(ALICE Collaboration), JHEP **09** (2016) 164

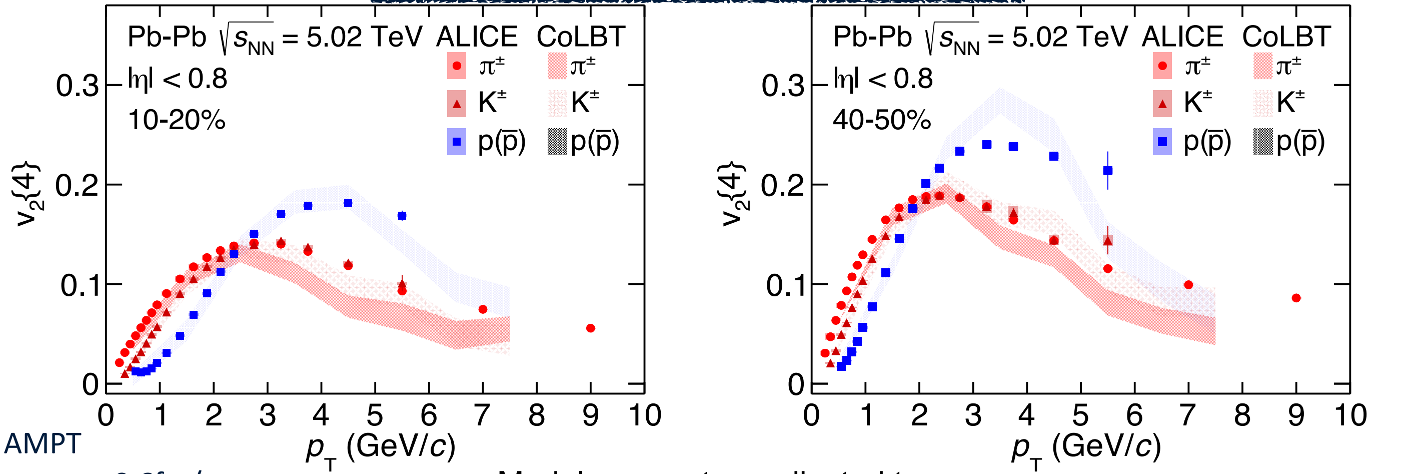




Rescattering has (probably) little effect

Attempt to describe all regions

W. Zhao *et al.*, Phys.Rev.Lett. 128 (2022) 2, 022302



- IS described by AMPT
- Hydro takes over at τ_0 = 0.6fm/*c*
  - η/s = 0.10 - w/o ζ/s
- T_{fo} = 150MeV → hadronic after-burner

Hadrons produced via

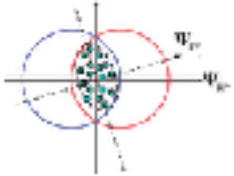
- Cooper-Frye prescription @ low p_T
- quark coalescence at intermediate p_T
- fragmentation at high p_T

Model parameters adjusted to reproduce (for charged particles in Pb-Pb)

- measured yields,
- p_T spectra,
- integrated v_n

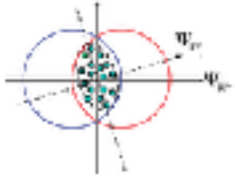
One of the few models that attempts to describe such measurements under a unified prescription

But there is more…: higher (odd) harmonics!



Reaction plane (Ψ_{RP}) → Participant (symmetry) plane Ψ_n

But there is more…: higher (odd) harmonics!

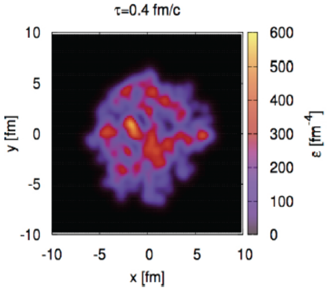


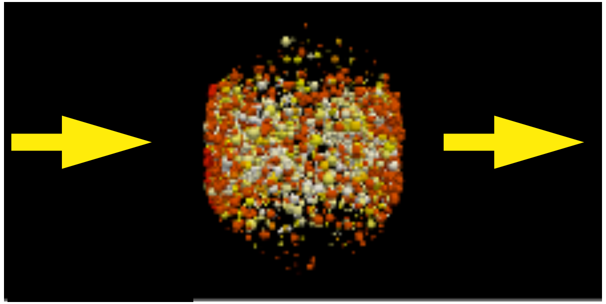
Reaction plane (Ψ_{RP}) → Participant (symmetry) plane Ψ_n

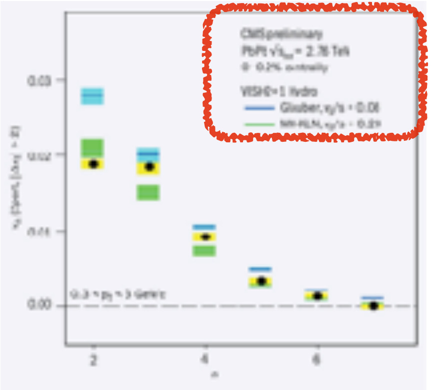
Initial state fluctuations

transferred via the low viscosity QGP

into final state correlations (higher, odd harmonics)



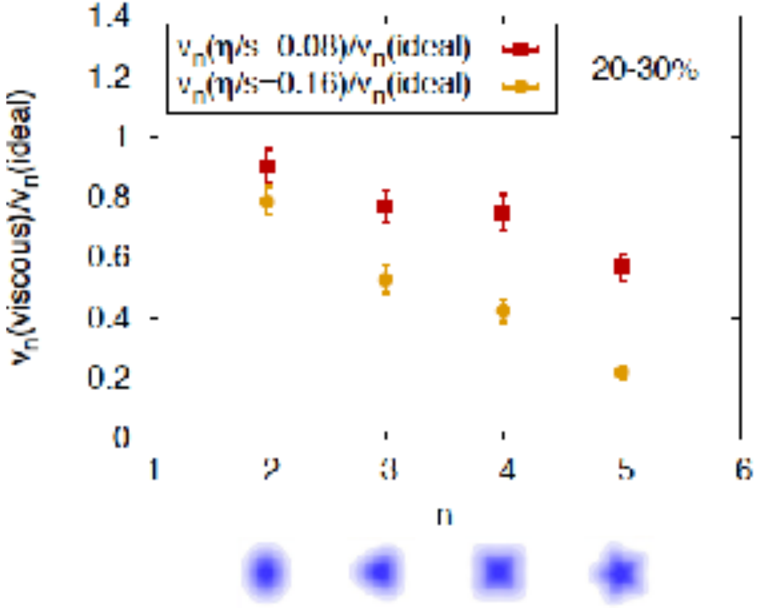




- Higher harmonics represent modulations in smaller spatial scales
  - More sensitive probes of the QGP transport properties
  - Unique tool to constrain initial state fluctuations

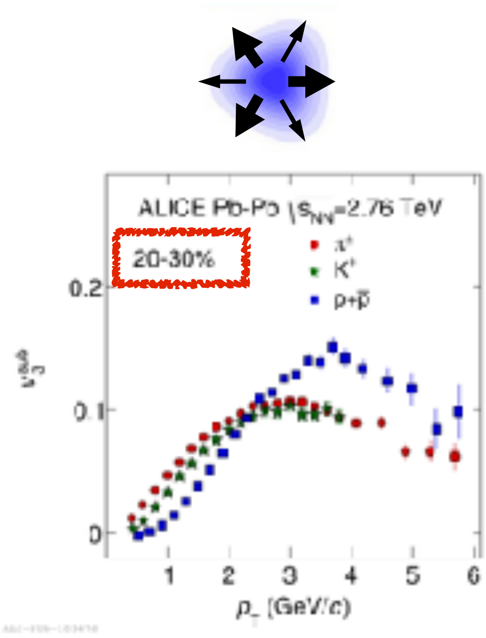
Effect of viscous corrections on higher harmonics

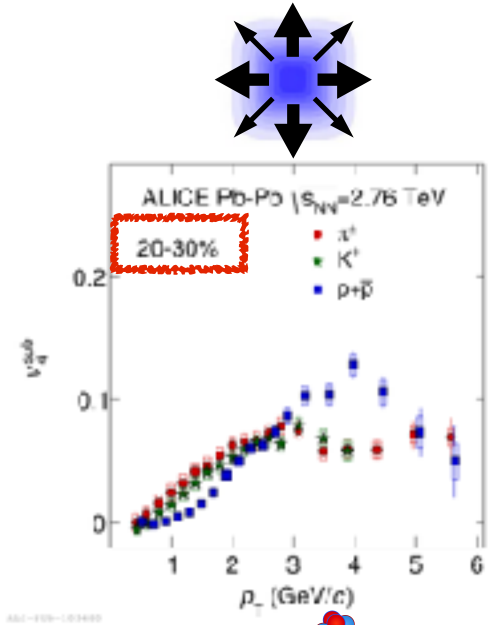
B. Schenke *et al.*, Phys.Rev. **C85** (2012) 024901

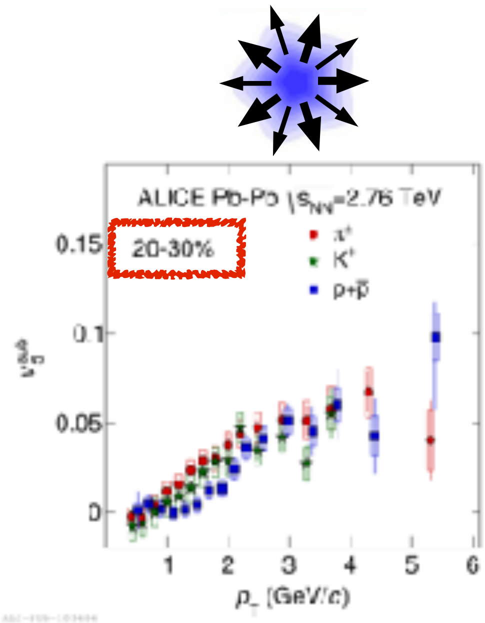


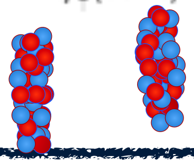
Relative decrease might change if different IS model is used but the trend vs harmonic is qualitatively the same

Higher harmonics at work



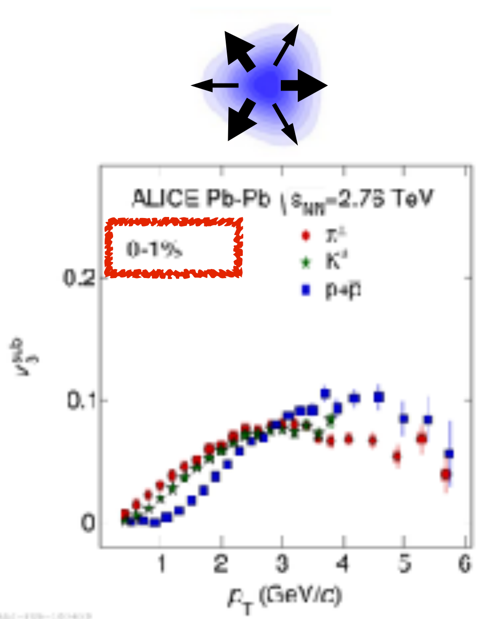


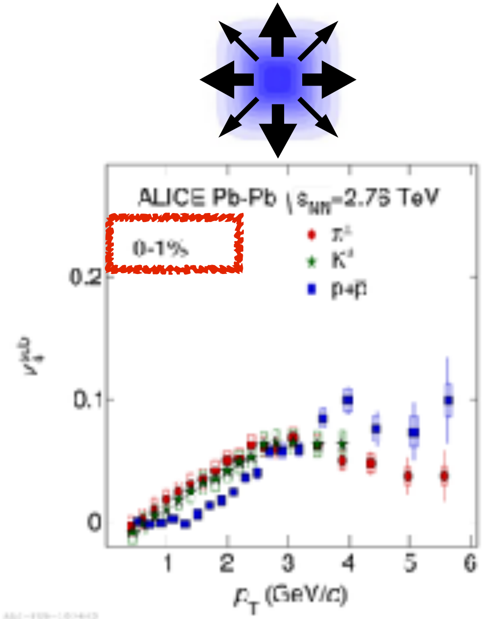


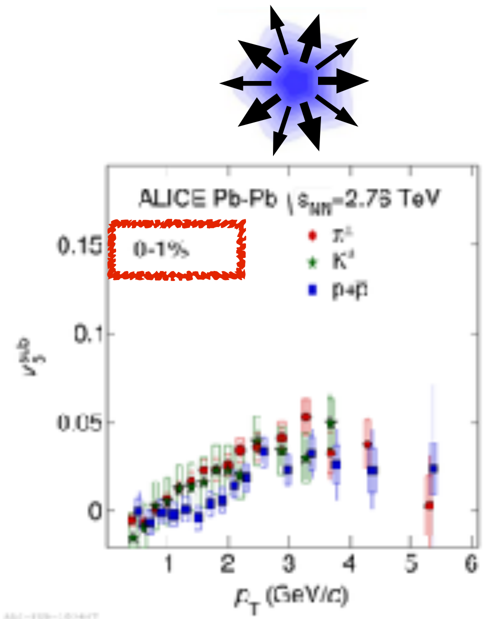


B. Abelev *et al.* (ALICE Collaboration), JHEP **09** (2016) 164

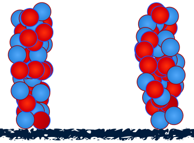
Higher harmonics at work in ultra-central events







Same features for different v_n (up to v_5!) even for ultra-central collisions

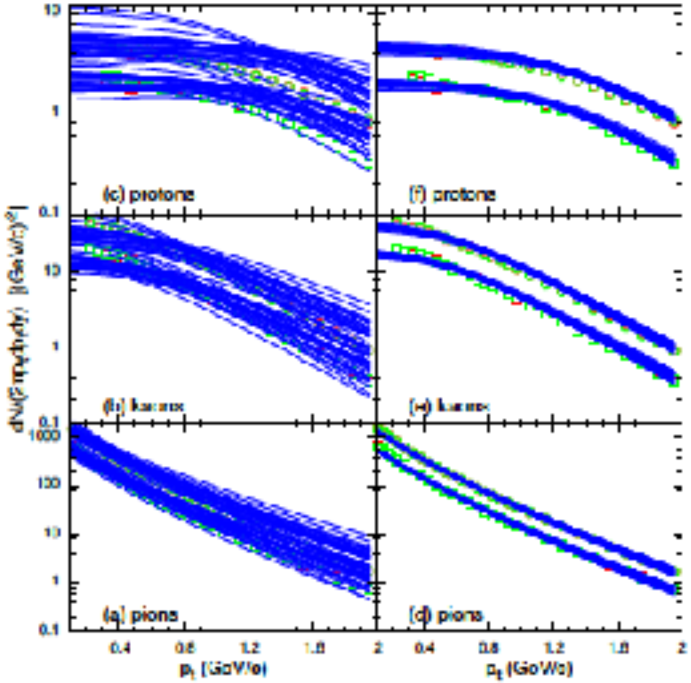


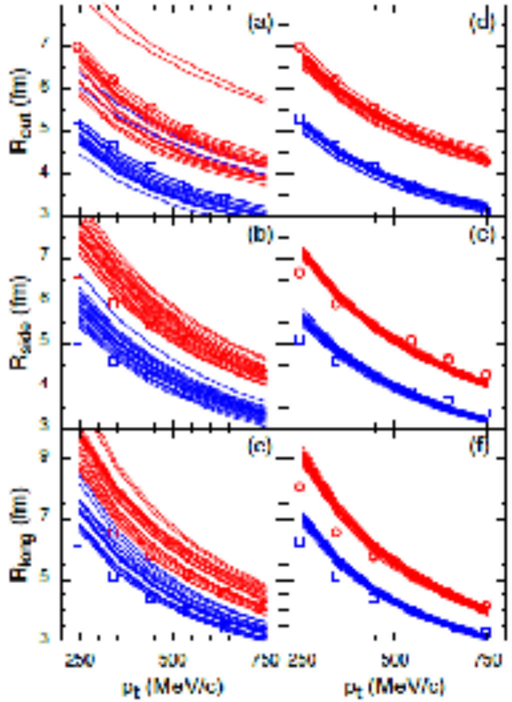
B. Abelev *et al*. (ALICE Collaboration), JHEP **09** (2016) 164

From qualitative to quantitative

EOS Constrains

S.Pratt *et al.*, Phys. Rev. Lett. **114**, (2015) 202301





Model parameters

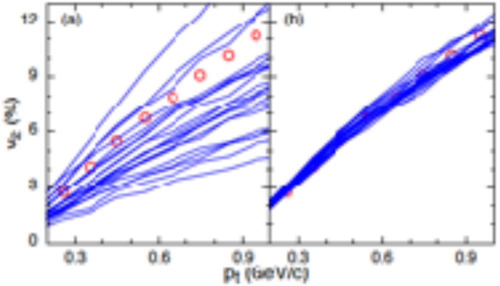
Experimental data

Priors

$$P(\mathbf{x}|\mathbf{y}_{\text{exp.}}) = \frac{P(\mathbf{y}_{\text{exp.}}|\mathbf{x})P(\mathbf{x})}{P(\mathbf{y}_{\text{exp.}})}$$

Posterior distribution

Normalisation ("Bayesian evidence")

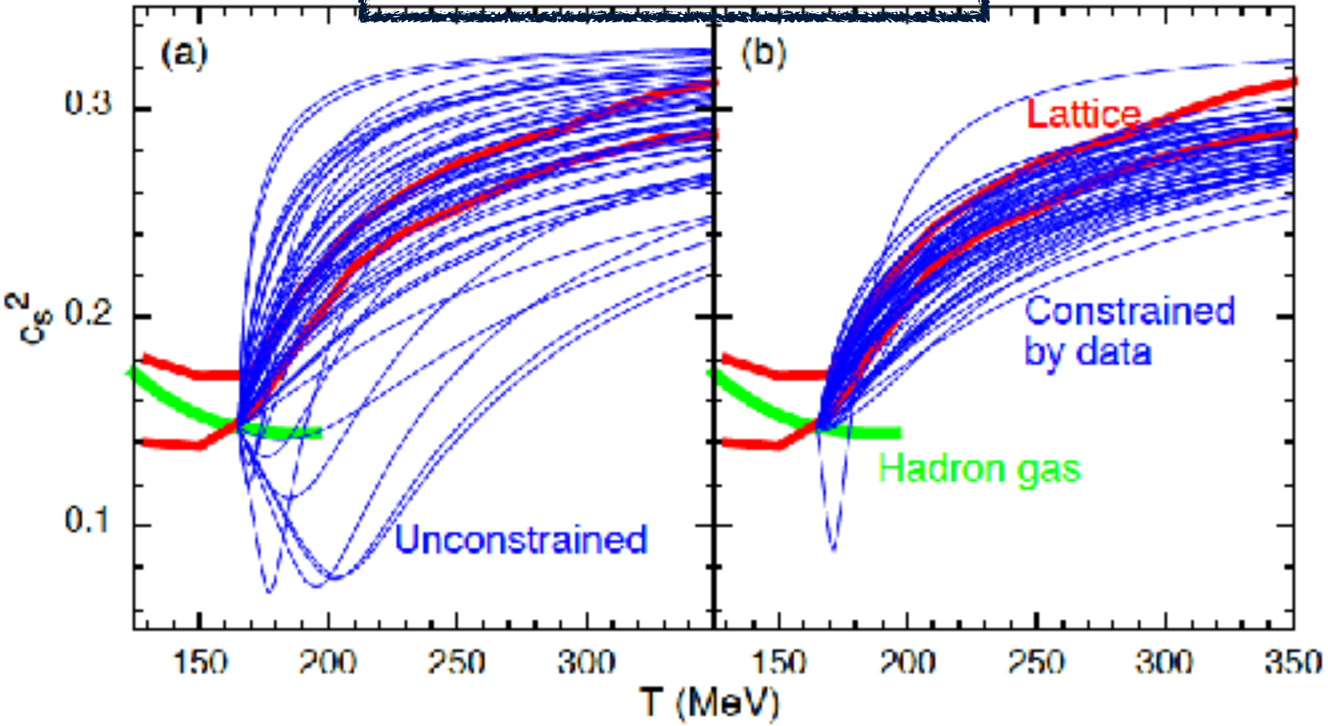


One of the first attempts for a global fit on data

EOS Constrains

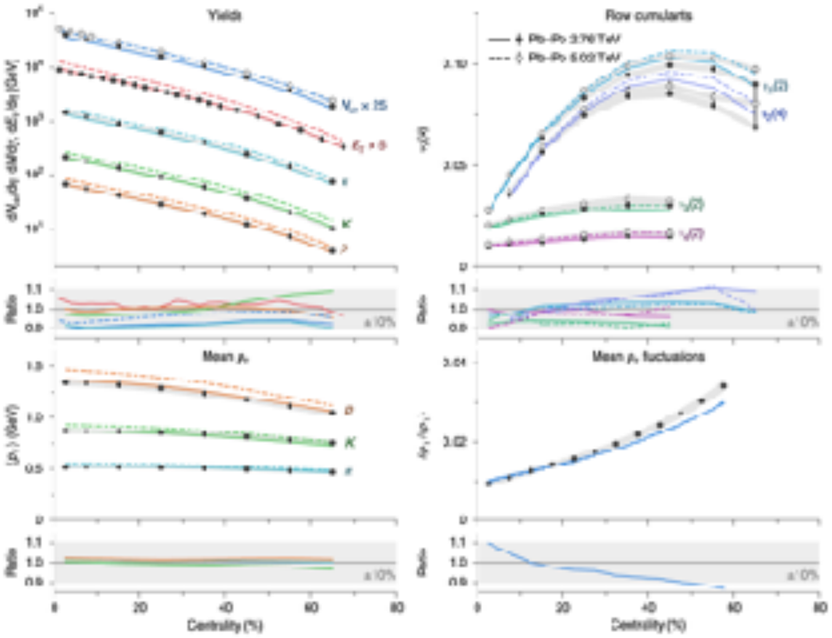
S.Pratt *et al*., Phys. Rev. Lett. **114**, (2015) 202301

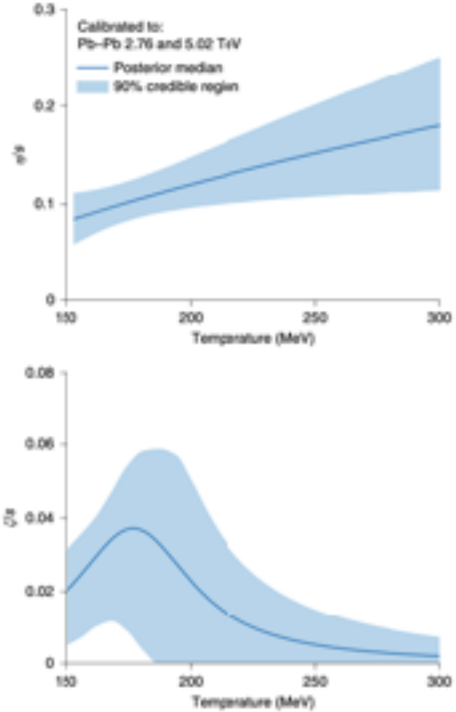
$$c_s^2 = \frac{\partial P}{\partial \epsilon}$$

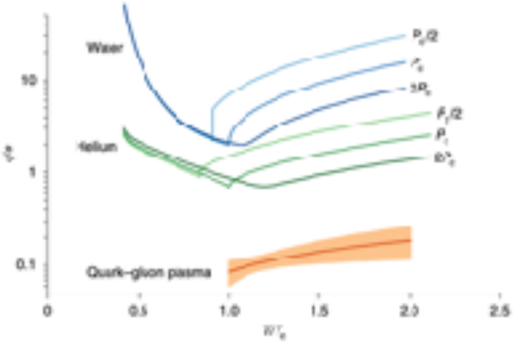


Transport properties constrains

J. E. Bernhard *et al.*, Nature Phys. 15, 214 (2019)



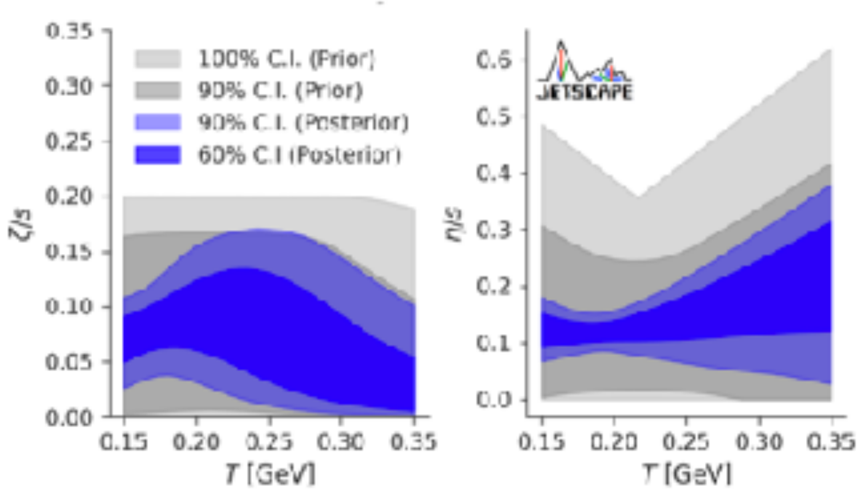




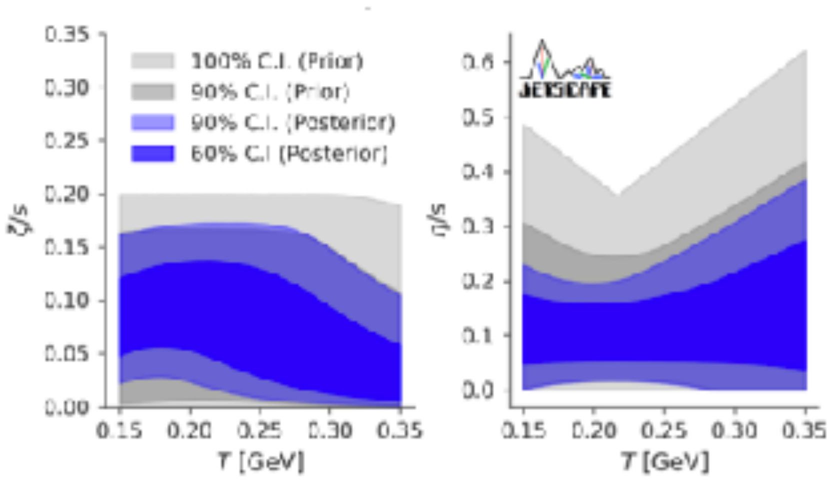
Transport properties constrains

(JETSCAPE Collaboration) Phys. Rev. C 103, 054904 (2021)

Posterior from LHC data



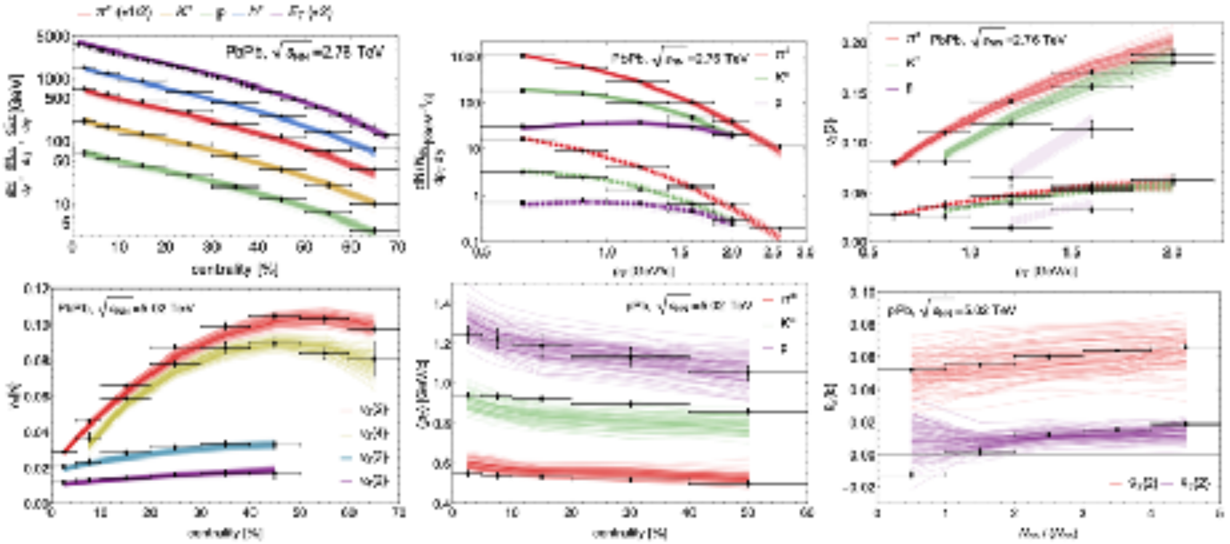
Posterior from RHIC data

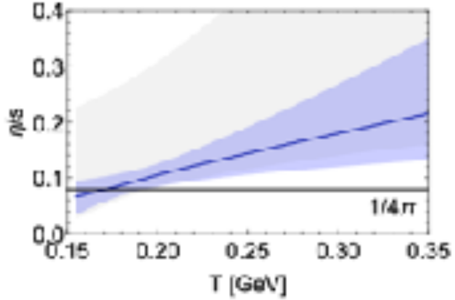


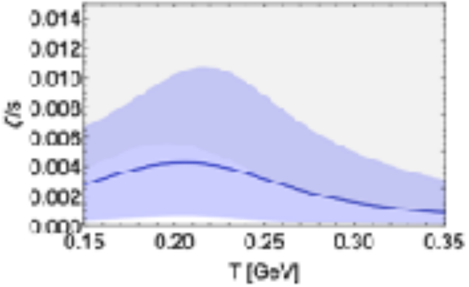
Coherent physics description of experimental data at various energies from a single model with a common set of parameters (except the initial energy density)

Estimates from Trajectum

G. Nijs *et al.*, *Phys.Rev.C* 103 (2021) 5, 054909

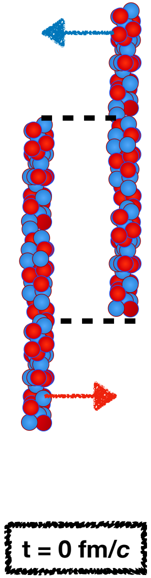






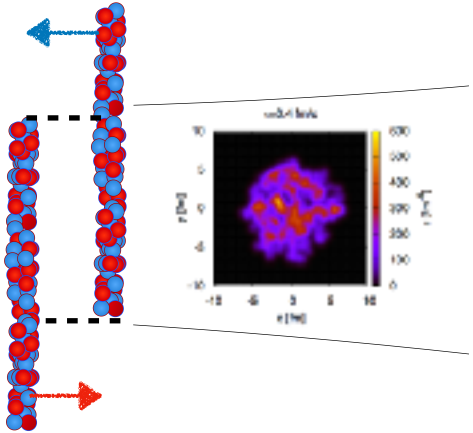
- First attempt to constrain transport coefficients by including p_T-differential quantities in a global fit + extract 2nd order coefficients

Lessons learned so far…



Lessons learned so far…

Initial stage



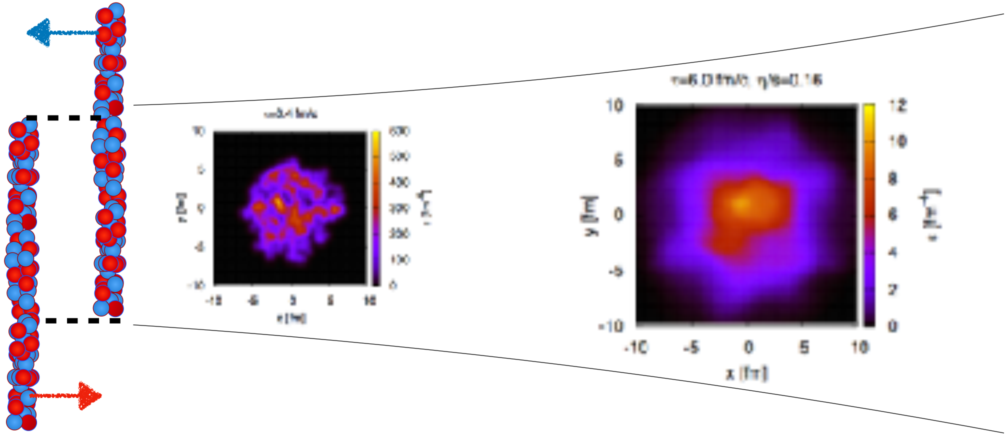
t = 0 fm/c

t < 1 fm/c

Pre-equilibrium

Lessons learned so far…

Initial stage	QGP evolution

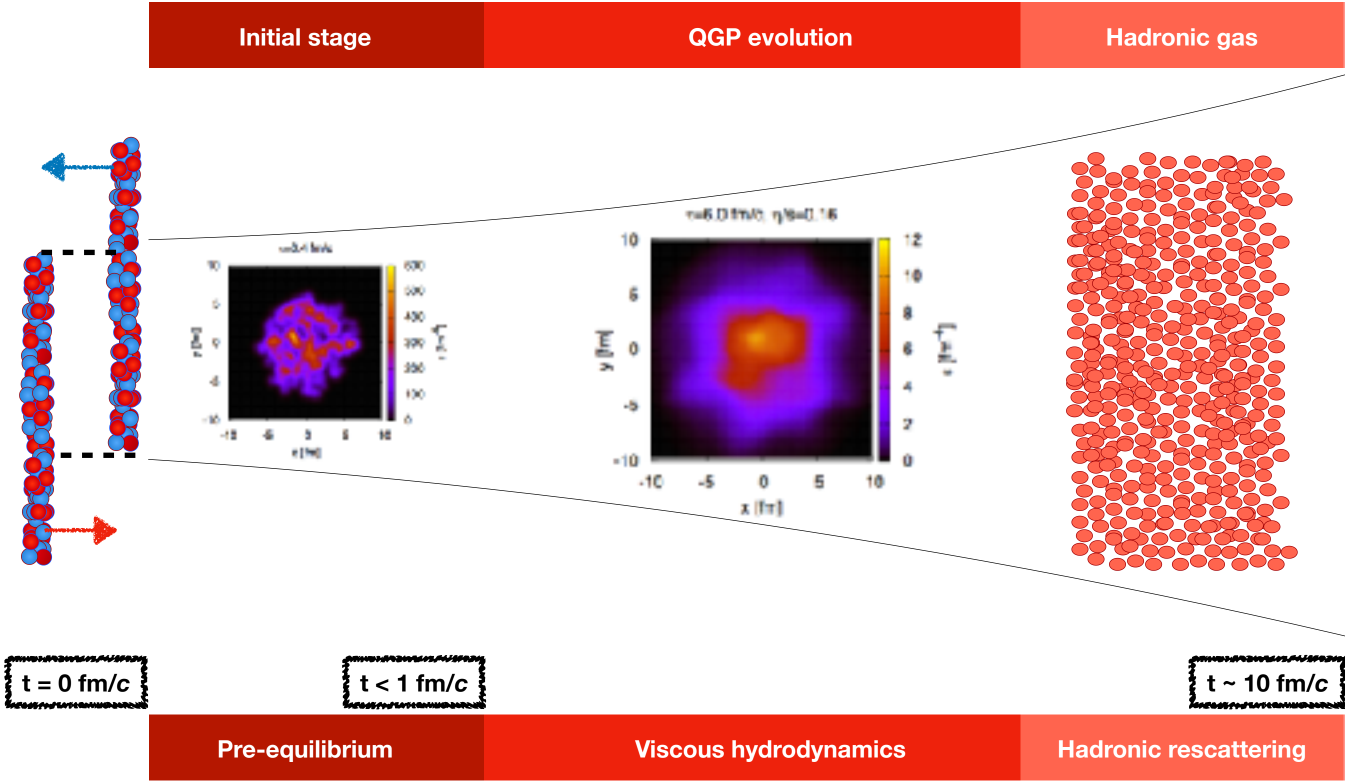


t = 0 fm/c

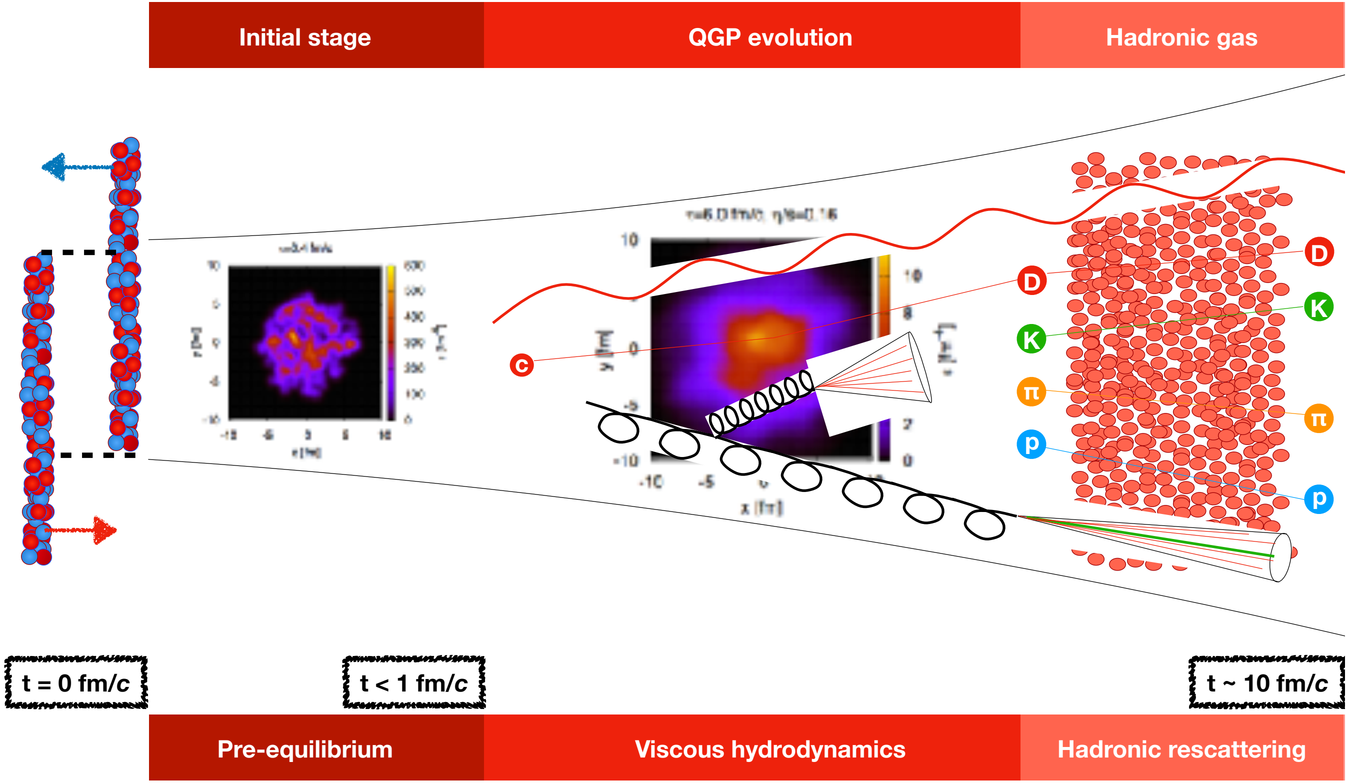
t < 1 fm/c

Pre-equilibrium	Viscous hydrodynamics

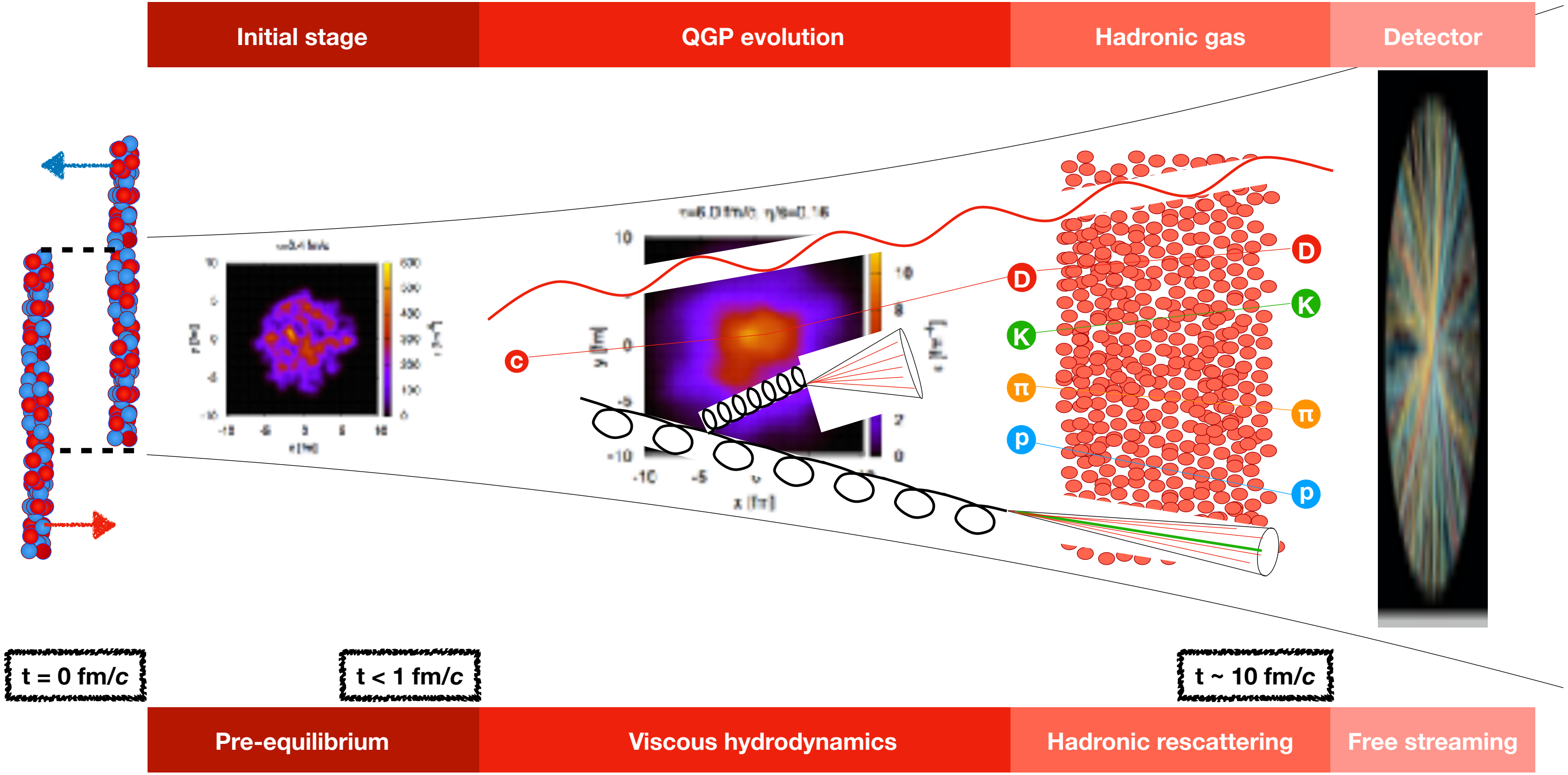
Lessons learned so far…



Lessons learned so far…

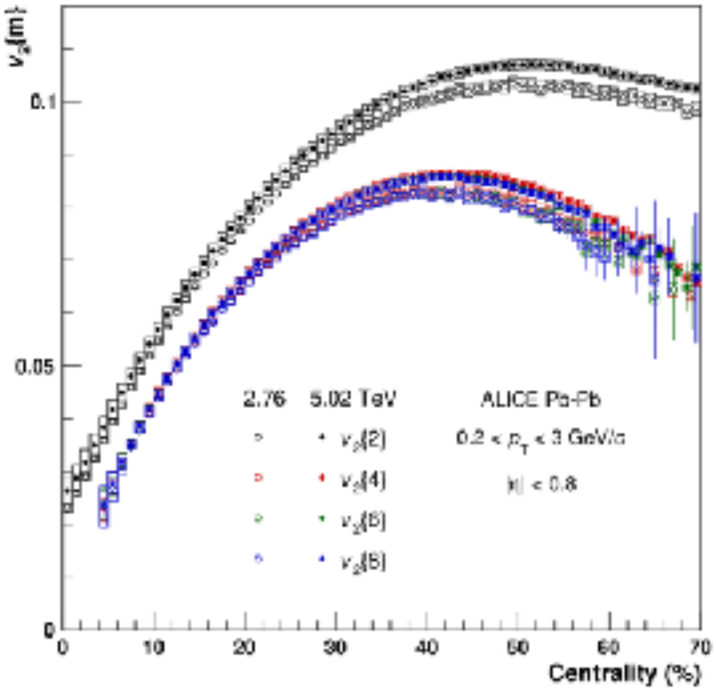


Lessons learned so far…



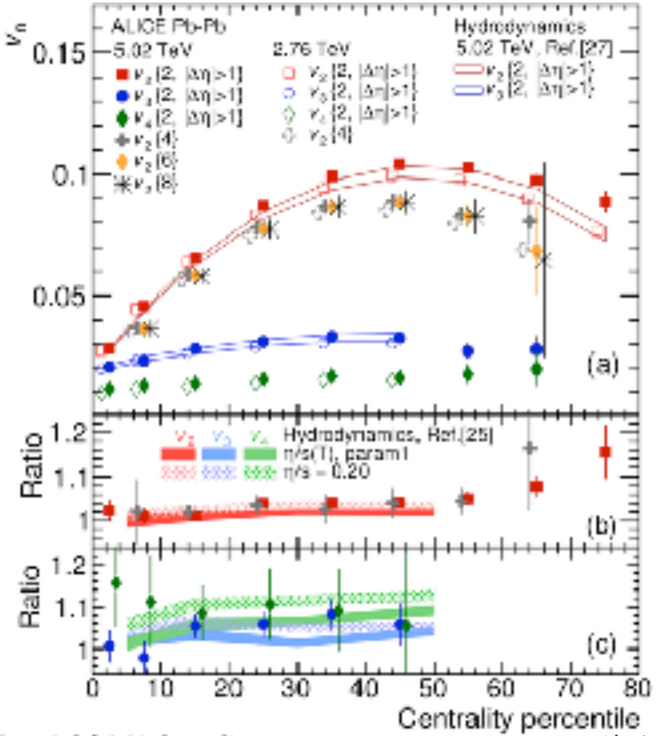
Temperature dependence of η/s

ALICE Collaboration, JHEP 07 (2018) 103



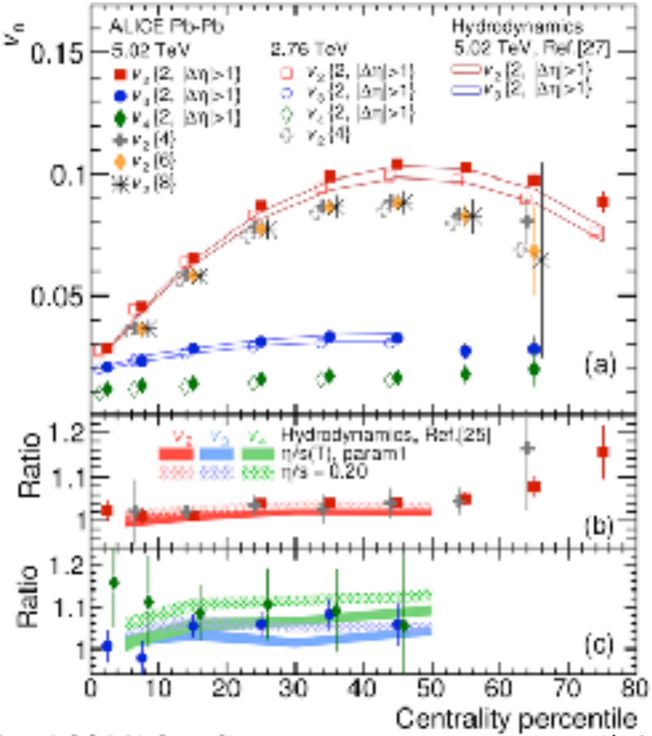
Temperature dependence of η/s

ALICE Collaboration, PRL 116 (2016) 132302

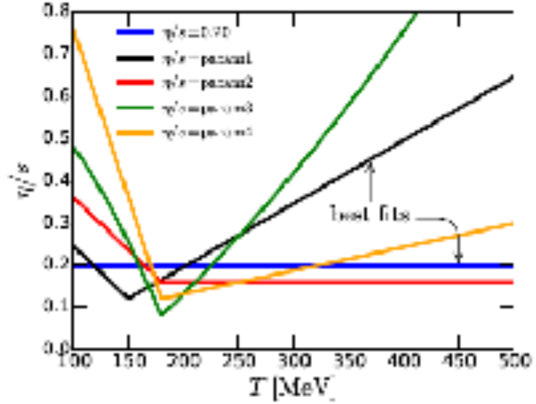


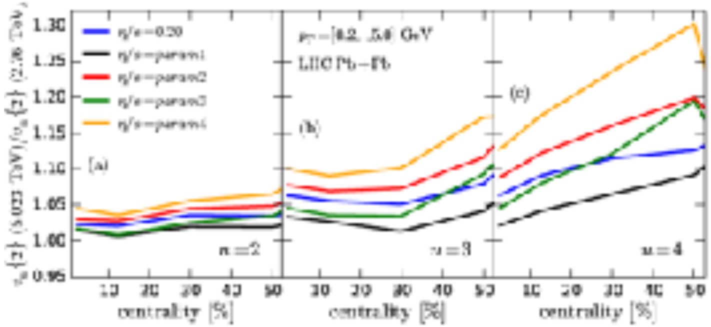
Temperature dependence of η/s

ALICE Collaboration, PRL 116 (2016) 132302



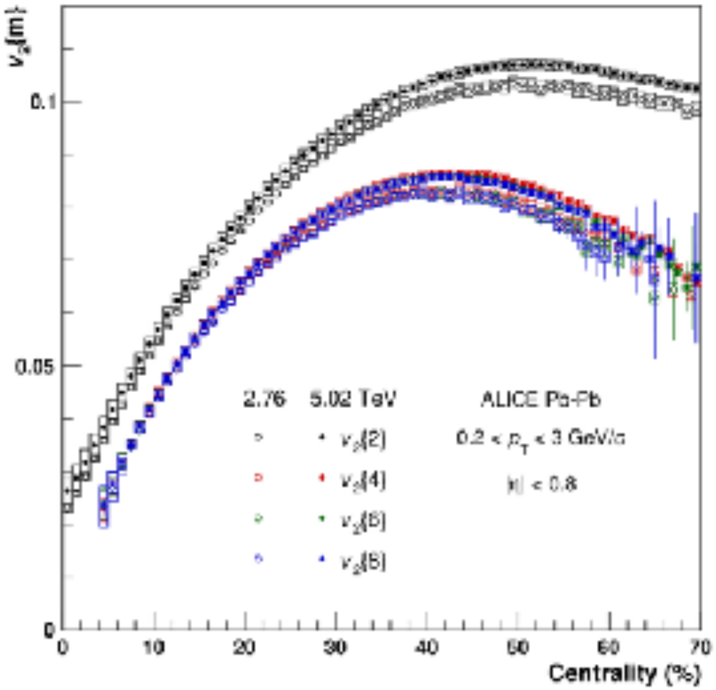
H. Niemi *et al.* Phys. Rev. C 93, 014912 (2016)





Flow fluctuations

ALICE Collaboration, JHEP 07 (2018) 103



Panos.Christakoglou@maastrichtuniversity.nl

Flow fluctuations

ALICE Collaboration, JHEP 07 (2018) 103

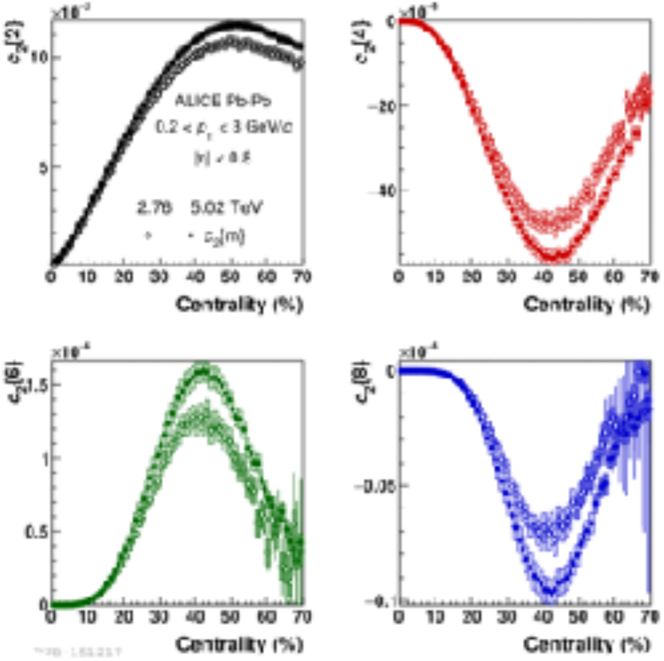
- What is the underlying probability distribution function (p.d.f.) of v_n, $P(v_n)$?
  - The magnitude of v_n is proportional (for n < 4; for n > 4 non-linear terms come into play) to ε_n
  - $P(v_n)$ ~ Bessel-Gaussian but (small) deviations have already been reported
    - Sensitivity to details of initial state!

$$v_n\{2\} = \sqrt{c_n\{2\}}$$

$$v_n\{4\} = \sqrt[4]{-c_n\{4\}}$$

$$v_n\{6\} = \sqrt[6]{\frac{1}{4}c_n\{6\}}$$

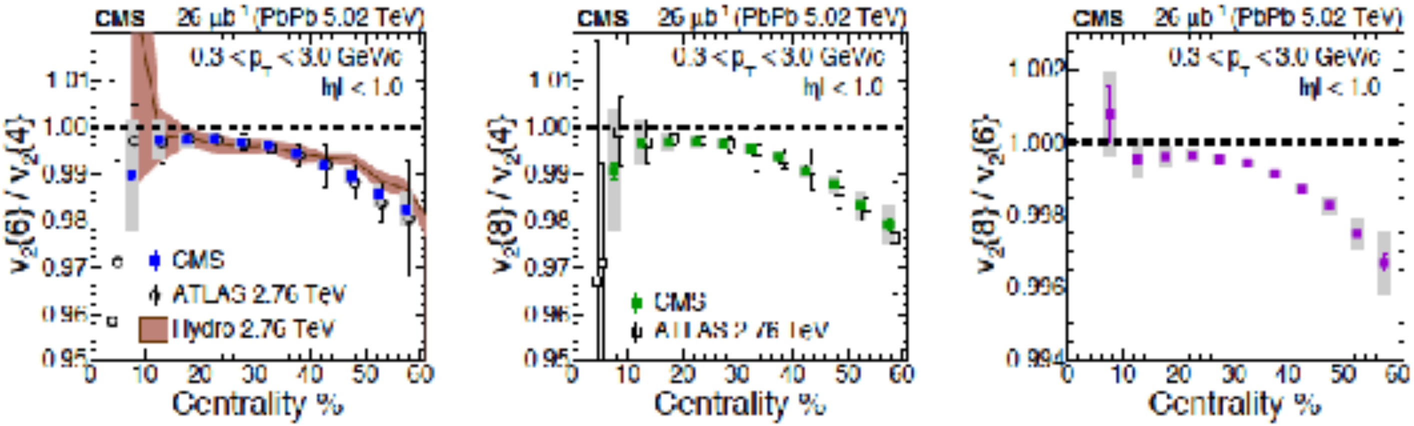
$$v_n\{8\} = \sqrt[8]{-\frac{1}{33}c_n\{8\}}$$



Flow fluctuations

Flow fluctuations

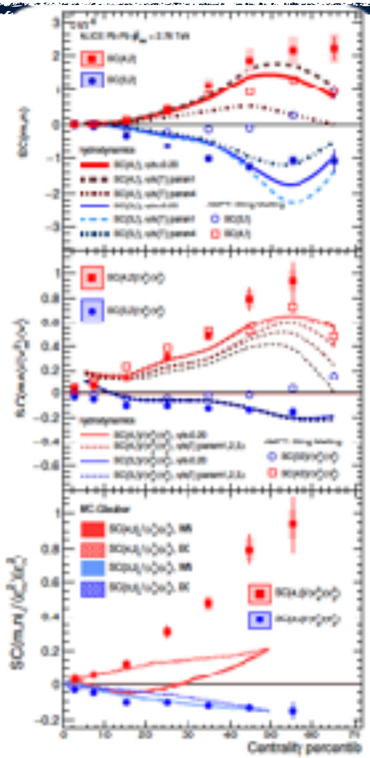
CMS Collaboration, Phys. Lett. **B789** (2019) 643



- Results do not show any significant energy dependence
  - Consistent with expectations for no significant differences in eccentricities between the two energies
- Ratios of multi-particle results deviate from unity for peripheral events
- Results for central events (fluctuations only region) are compatible with a Bessel-Gaussian $P(v_2)$
- Skewness estimated from the fine-splitting of $v_2\{m\}$

Correlations between harmonic amplitudes

ALICE Collaboration, Phys. Rev. Lett. **117**, (2016) 182301

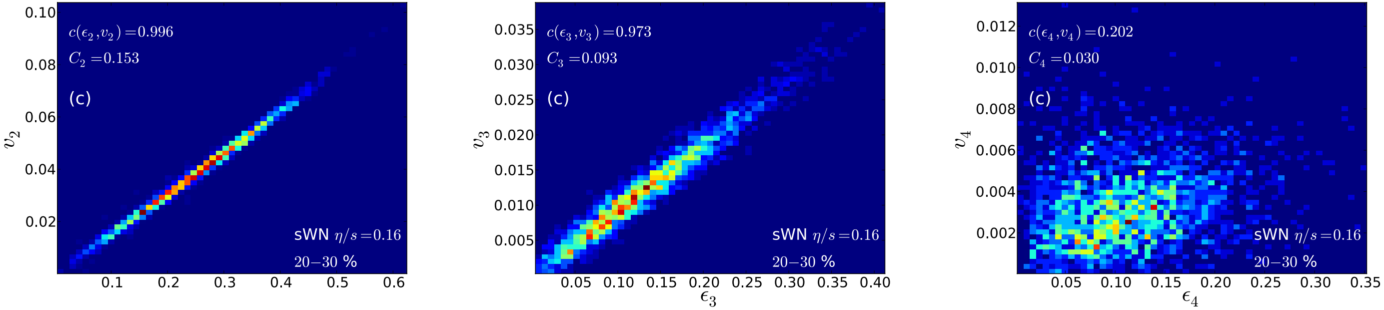


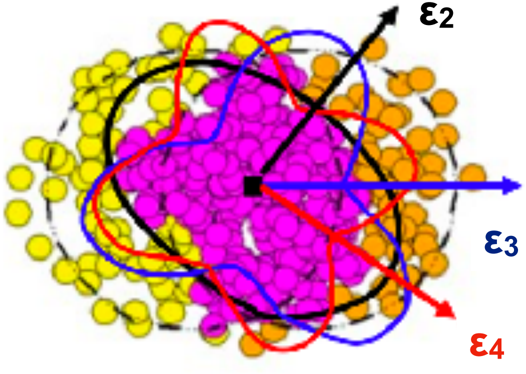
- Some new clever ways of disentangling the effects of the initial state from the transport properties of the QGP
  - Example: study symmetric cumulants (SC) ➡ probe correlations between the magnitudes of different flow harmonics
  - Magnitudes of v_2 and v_3 and anti-correlated
  - Magnitudes of v_2 and v_4 and correlated

- Normalised symmetric cumulants (NSC) cancels out the dependence of vn on IS or transport properties
  - NSC(3,2) sensitive to IS ➡ v_3 mainly dominated by IS fluctuations
  - NSC(4,2) sensitive to transport properties ➡ v_4 has a non-linear contribution from v_2

Non-linear flow modes

H. Niemi *et al.*, Phys.Rev. C87 (2013), 054901





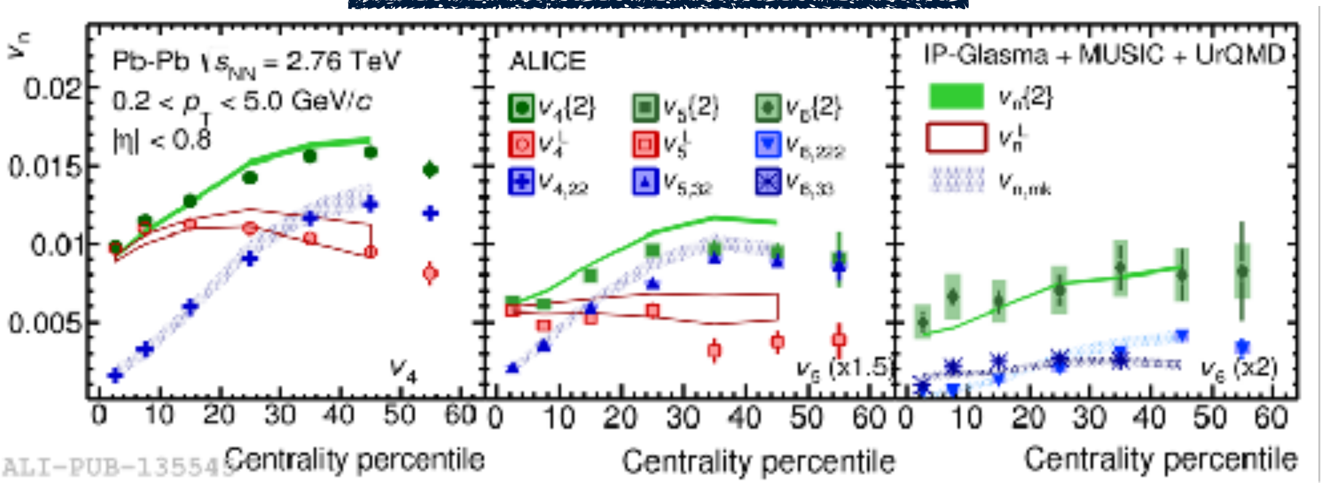
$$V_n = V_n^{\mathrm{L}} + V_n^{\mathrm{NL}} \quad (n > 3)$$

Linear response

Non-linear response

Non-linear flow modes: charged particles

(ALICE Collaboration) Phys.Lett. **B773** (2017) 68



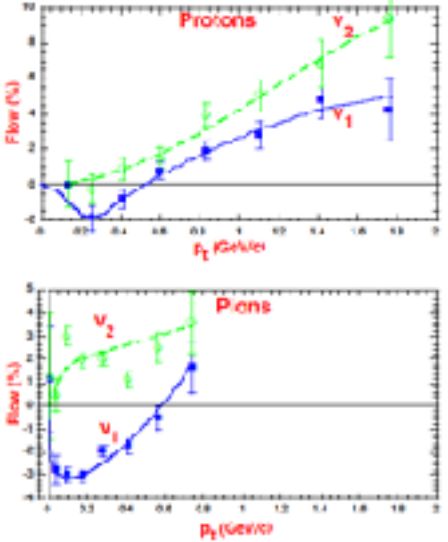
$$v_4^{\mathrm{L}} = \sqrt{v_4^2 - v_{4,22}^2}$$

$$v_5^{\mathrm{L}} = \sqrt{v_5^2 - v_{5,32}^2}$$

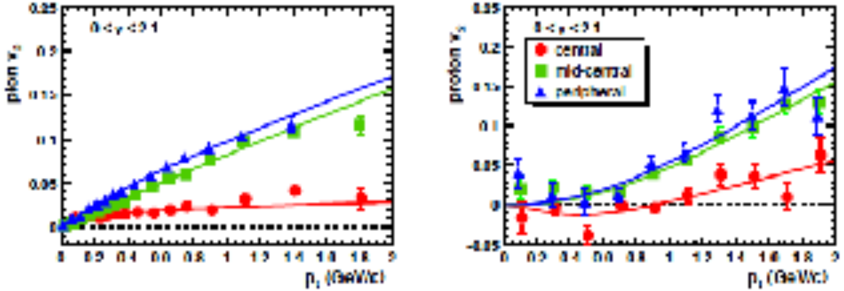
$$V_4 = V_{4L} + \chi_{422} V_2^2,$$
$$V_5 = V_{5L} + \chi_{523} V_2 V_3,$$
$$V_6 = V_{6L} + \chi_{624} V_2 V_{4L} + \chi_{633} V_3^2 + \chi_{6222} V_2^3,$$
$$V_7 = V_{7L} + \chi_{725} V_2 V_{5L} + \chi_{734} V_3 V_{4L} + \chi_{7223} V_2^2 V_3$$

We’ve come a long way…from this

(NA49 Collaboration) Phys.Rev.Lett. 80 (1998) 4136

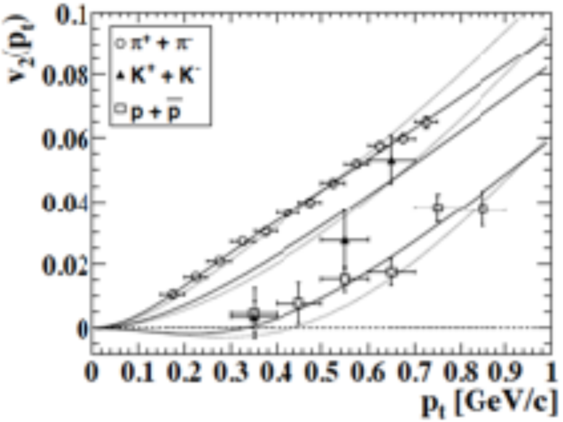


(NA49 Collaboration) Phys.Rev. C68 (2003) 034903

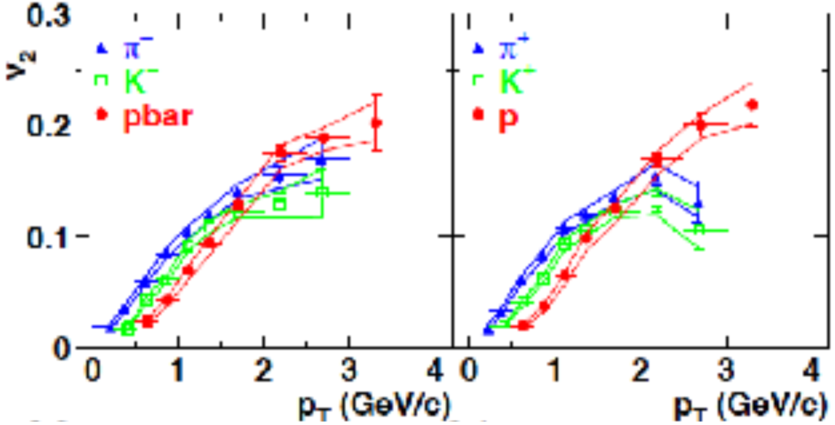


We've come a long way…to this

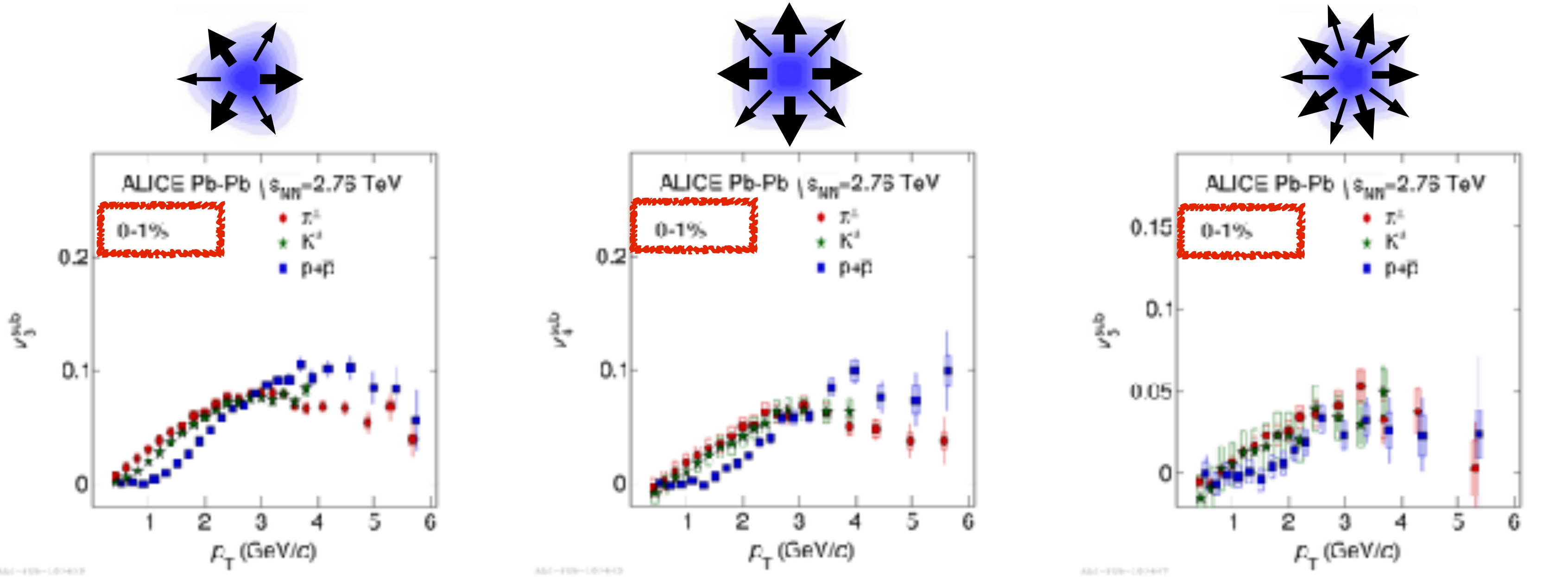
(STAR Collaboration): Phys. Rev. Lett. 87 (2001) 182301



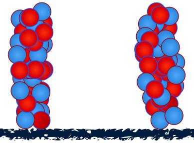
(PHENIX Collaboration): Phys.Rev.Lett.91, 182301,2003



We’ve come a long way…and now to this



Same features for different v_n (up to v_5!) even for ultra-central collisions

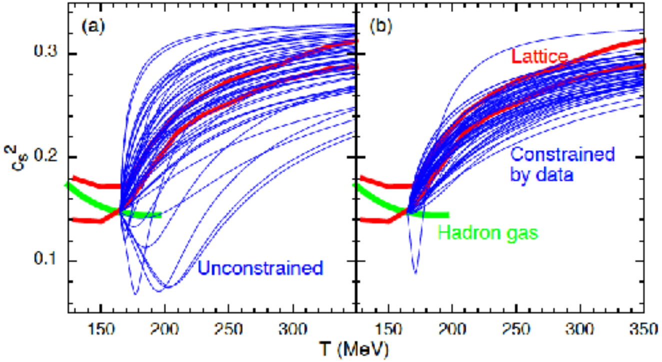


B. Abelev *et al*. (ALICE Collaboration), JHEP **09** (2016) 164

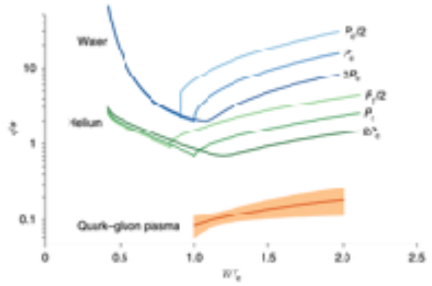
Panos.Christakoglou@maastrichtuniversity.nl

We’ve come a long way…and now to this

S.Pratt *et al.*, Phys. Rev. Lett. **114**, (2015) 202301

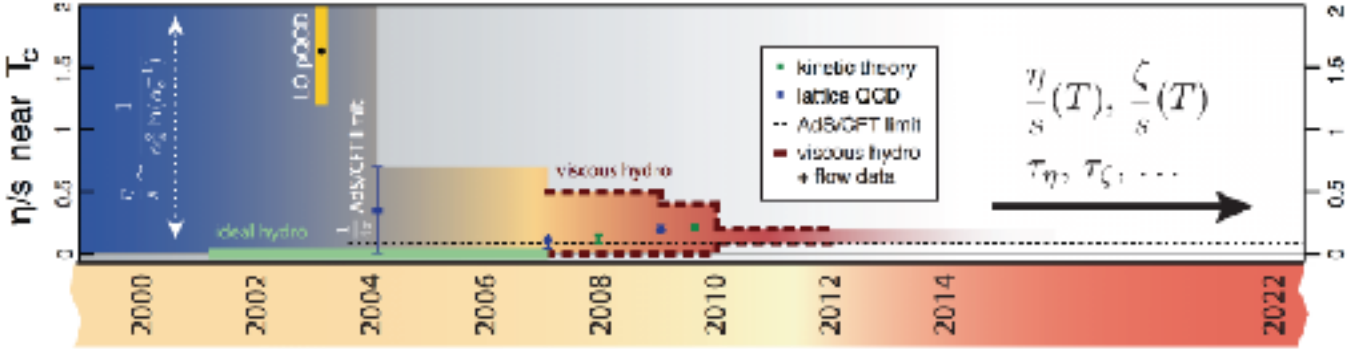


J. E. Bernhard *et al.*, Nature Phys. 15, 214 (2019)

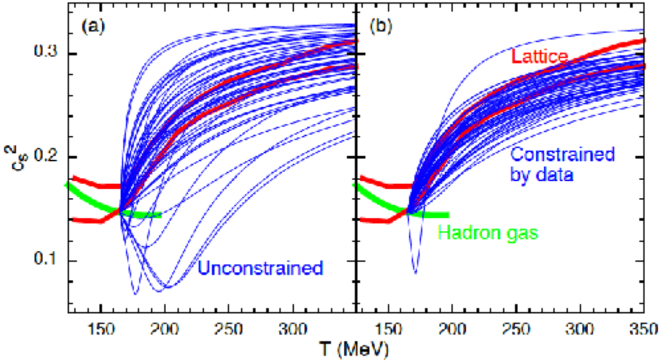


Panos.Christakoglou@maastrichtuniversity.nl

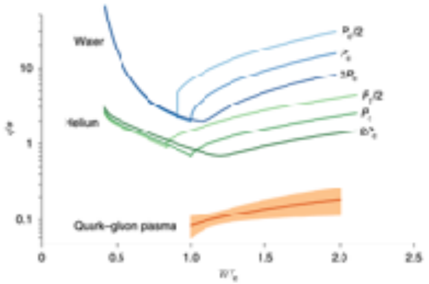
We've come a long way...and now to this



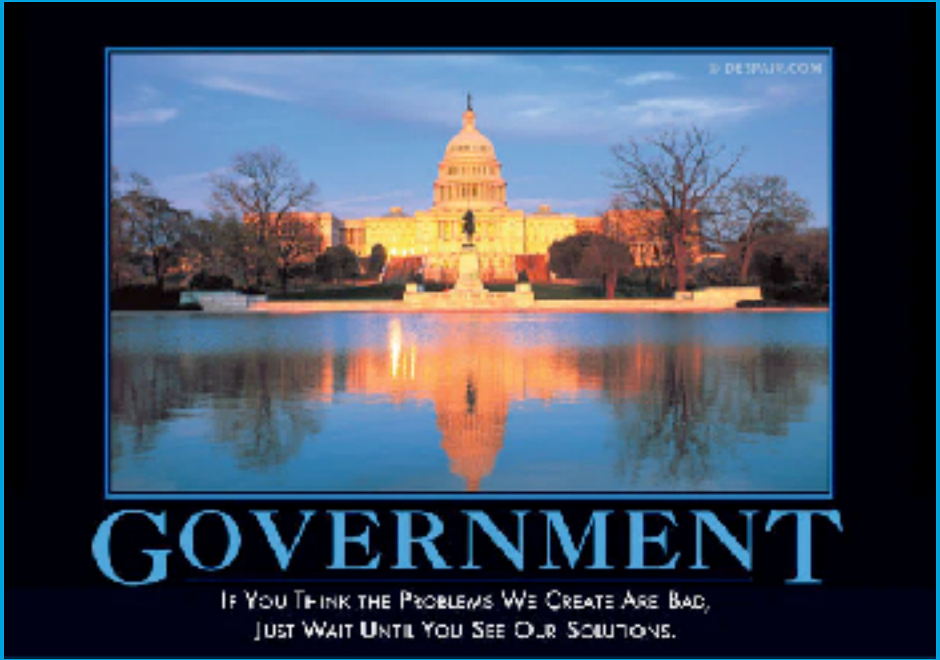
S.Pratt *et al.*, Phys. Rev. Lett. **114**, (2015) 202301



J. E. Bernhard *et al.*, Nature Phys. 15, 214 (2019)



Surprises...

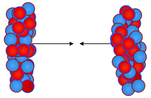


GOVERNMENT
If You Think the Problems We Create Are Bad,
Just Wait Until You See Our Solutions.

But there are also surprises…

Pb-Pb
$\sqrt{s_{NN}}$ = 2.76 TeV
$\sqrt{s_{NN}}$ = 5.02 TeV

Xe-Xe
$\sqrt{s_{NN}}$ = 5.44 TeV



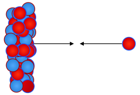
But there are also surprises…

Pb-Pb
$\sqrt{s_{NN}}$ = 2.76 TeV
$\sqrt{s_{NN}}$ = 5.02 TeV

Xe-Xe
$\sqrt{s_{NN}}$ = 5.44 TeV

p-Pb
$\sqrt{s_{NN}}$ = 5.02 TeV
$\sqrt{s_{NN}}$ = 8 TeV

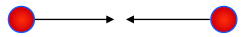
p-Au, d-Au, He^3-Au
$\sqrt{s_{NN}}$ = 0.2 TeV



But there are also surprises…

Pb-Pb
$\sqrt{s_{NN}}$ = 2.76 TeV
$\sqrt{s_{NN}}$ = 5.02 TeV

Xe-Xe
$\sqrt{s_{NN}}$ = 5.44 TeV



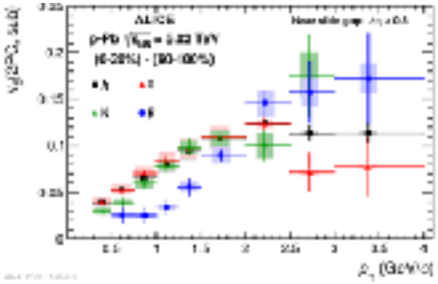
p-Pb
$\sqrt{s_{NN}}$ = 5.02 TeV
$\sqrt{s_{NN}}$ = 8 TeV

p-Au, d-Au, He^3-Au
$\sqrt{s_{NN}}$ = 0.2 TeV

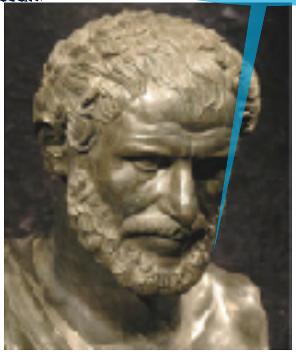
pp
$\sqrt{s}$ = 2.76 TeV
$\sqrt{s}$ = 5.02 TeV
$\sqrt{s}$ = 7 TeV
$\sqrt{s}$ = 8 TeV
$\sqrt{s}$ = 13 TeV

But there are also surprises…

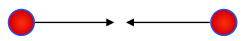
(ALICE Collaboration) Phys. Lett. **B726**, (2013) 164



Τα πάντα ρει…(everything flows)



Ηράκλειτος (Heraclitus) ~535 - 475 BC



p-Pb
$\sqrt{s_{NN}}$ = 5.02 TeV
$\sqrt{s_{NN}}$ = 8 TeV

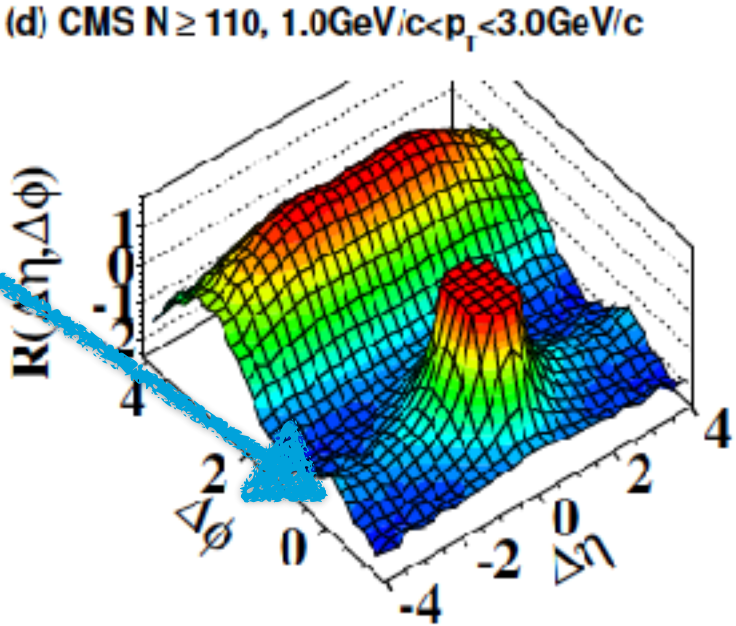
p-Au, d-Au, He^3-Au
$\sqrt{s_{NN}}$ = 0.2 TeV

pp
$\sqrt{s}$ = 2.76 TeV
$\sqrt{s}$ = 5.02 TeV
$\sqrt{s}$ = 7 TeV
$\sqrt{s}$ = 8 TeV
$\sqrt{s}$ = 13 TeV

Where things got started…

(CMS Collaboration) JHEP 09, (2010) 091

Ridges in pp collisions: when pp collisions stopped being just a reference for the heavy-ion physics programs

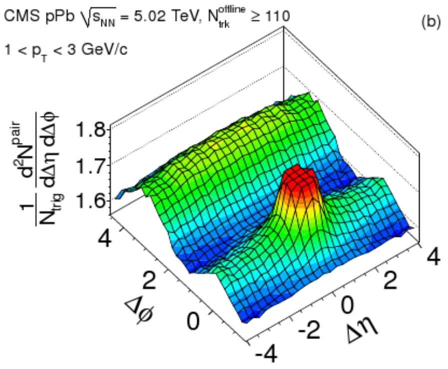


pp collisions @ √s = 7 TeV

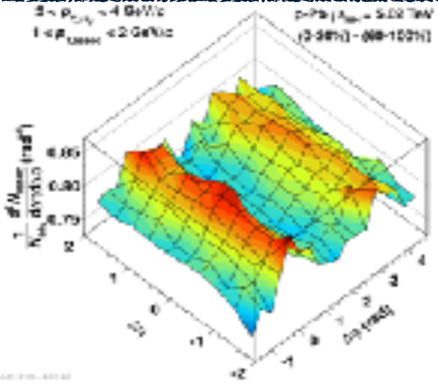
It should not have been a surprise: ridges in p-Pb collisions

It should not have been a surprise: ridges in p-Pb collisions

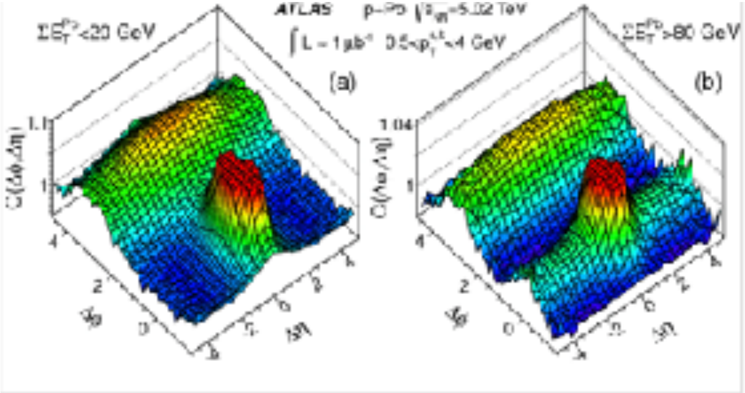
(CMS Collaboration) Phys. Lett. **B718**, (2013) 795



ALICE Collaboration: Phys. Lett. **B719**, (2013) 29

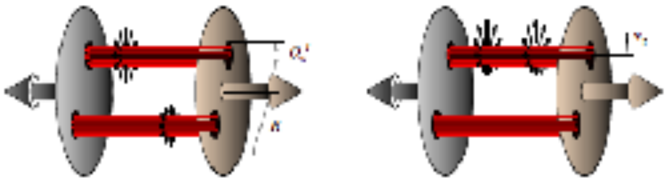


ATLAS Collaboration, Phys. Rev. Lett. **110**, (2013) 182302

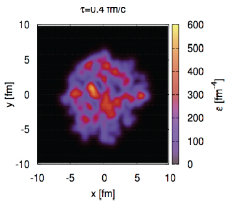


Where do these effects come from?

- Initial state effects → "CGC picture"
  - Particles are produced with their momentum-space correlations already "built-in"
  - Target and projectiles described as dense coloured objects
  - Anisotropy induced by scattering off domains of color-electric and magnetic fields that fluctuate from event to event
  - Gluon fields + their evolution/interactions described by classical YM equations



VS

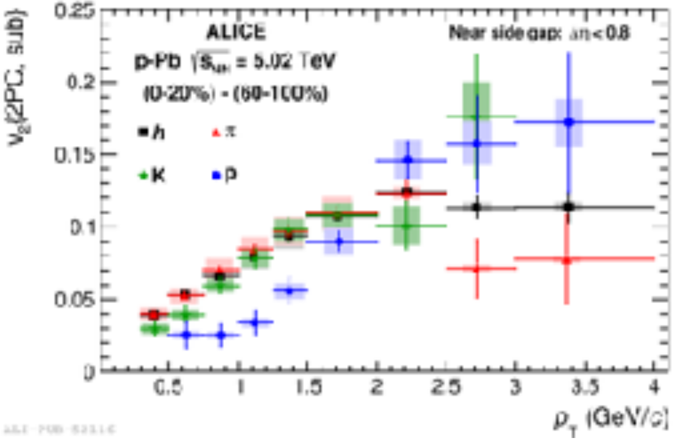


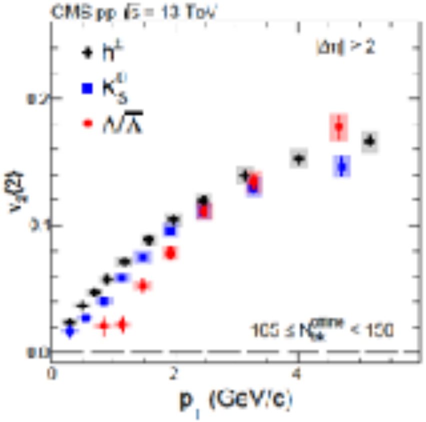
- Final state effects → "hydrodynamical picture"
  - Particles get their momentum-space correlations from final state interactions during the evolution of the system
    - Conversion of structures/correlations in coordinate space into structures/correlations in momentum space
  - Applicability of hydro
    - $\lambda_{mfp} \ll$ system size
    - $K_{n\theta} \ll 1$ (Knudsen number → ratio of micro to macroscopic scales e.g. relaxation time λ_{mfp} ~ vs inverse of expansion rate

Everything flows…

ALICE Collaboration, Phys. Lett. B726, (2013) 164

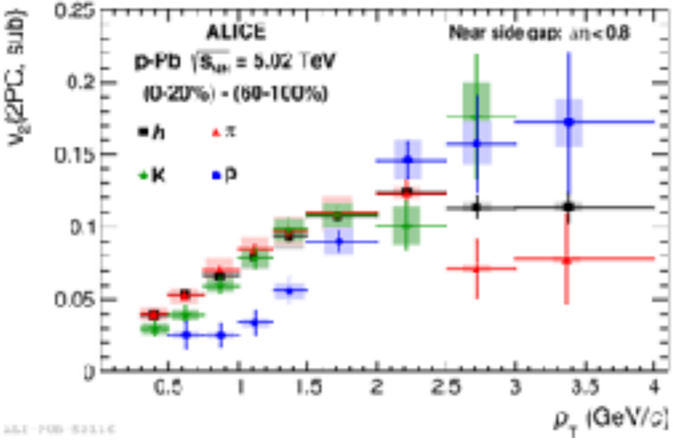
(CMS Collaboration) Phys. Lett. B 765 (2017) 193



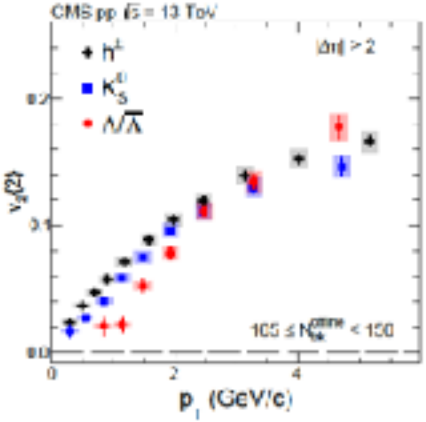


Everything flows…

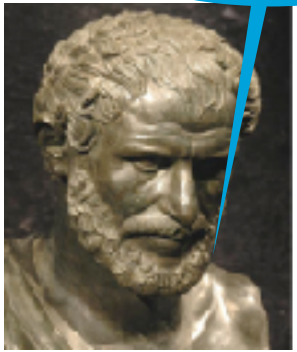
ALICE Collaboration, Phys. Lett. B726, (2013) 164



(CMS Collaboration) Phys. Lett. B 765 (2017) 193



Τα πάντα ρει…(everything flows)



Ηράκλειτος (Heraclitus) ~535 - 475 BC

Everything flows...

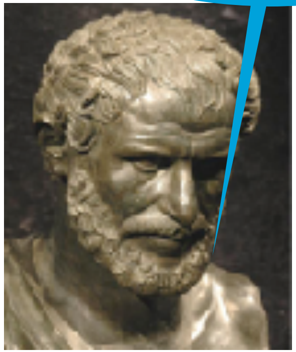
Even heavy flavour…
well at least charm

(CMS Collaboration) Phys. Rev. Lett. 121 (2018) 082301

Everything flows...

(CMS Collaboration) Phys. Rev. Lett. 121 (2018) 082301

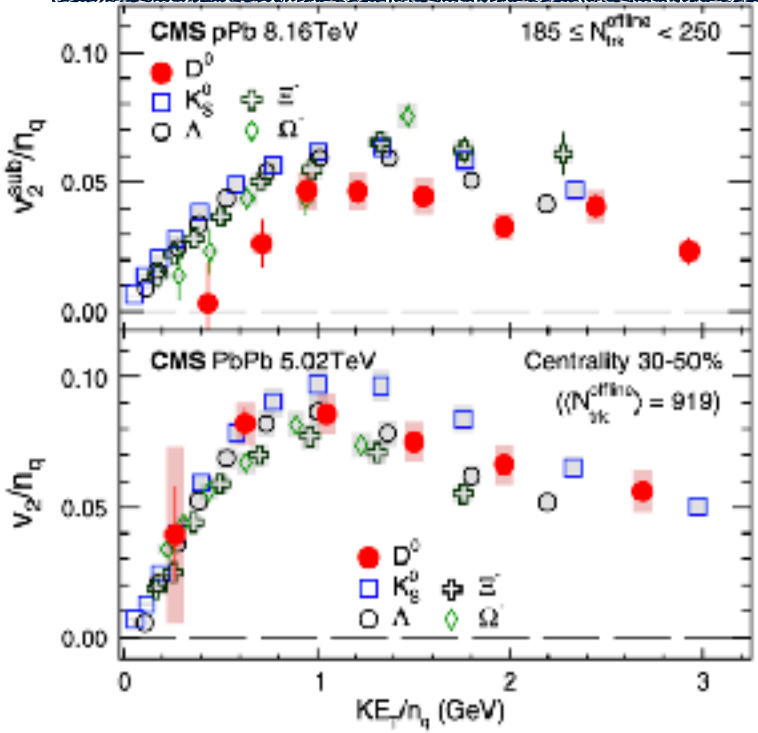
Even heavy flavour… well at least charm



Ηράκλειτος (Heraclitus) ~535 - 475 BC

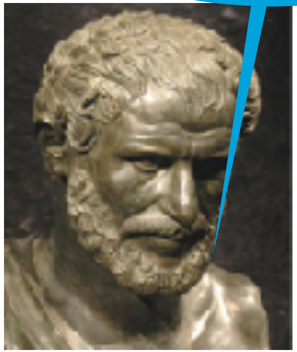
Everything flows…

(CMS Collaboration) Phys. Rev. Lett. 121 (2018) 082301



Even heavy flavour… well at least charm

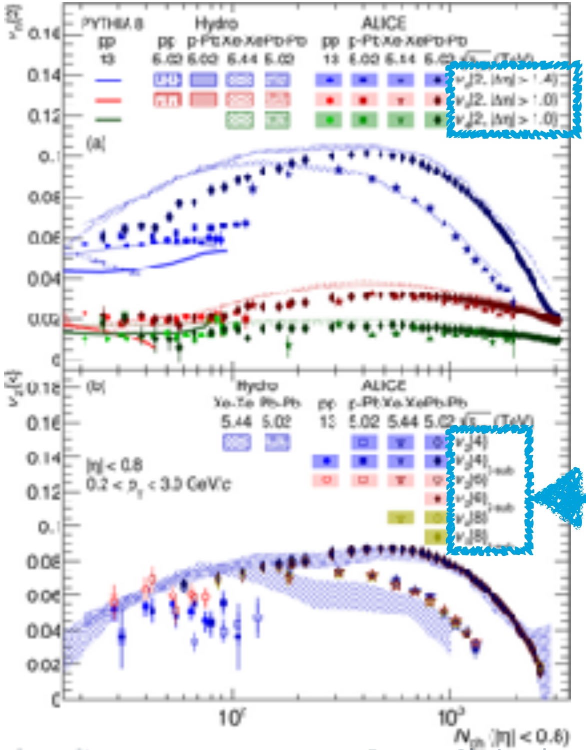
Τα πάντα ρει…(everything flows)



Ηράκλειτος (Heraclitus) ~535 - 475 BC

Everything flows…

(ALICE Collaboration) PRL123, 142301 (2019)



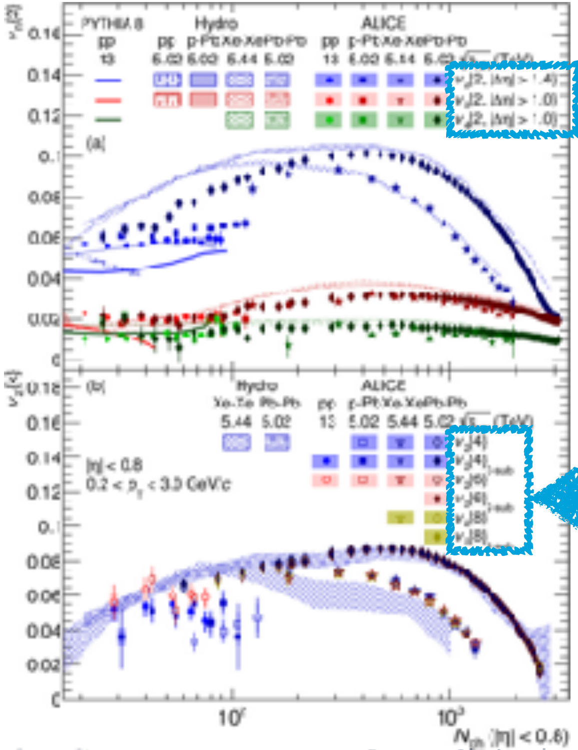
Correlations are characterised by their long range nature

Correlations shared between many particles

Panos.Christakoglou@maastrichtuniversity.nl

Everything flows...

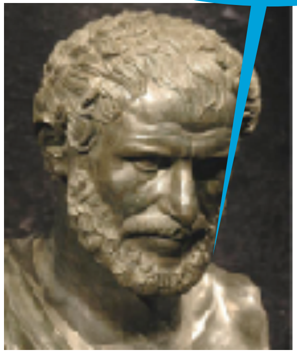
(ALICE Collaboration) PRL123, 142301 (2019)



Correlations are characterised by their long range nature

Correlations shared between many particles

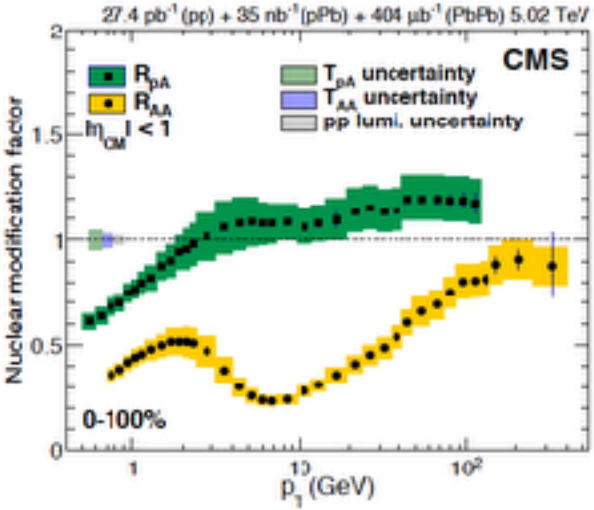
Τα πάντα ρει…(everything flows)



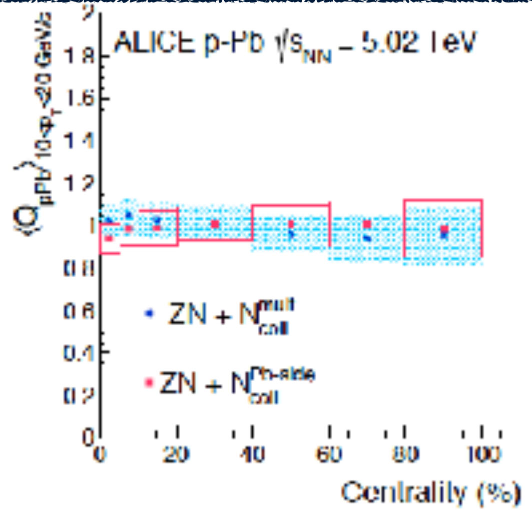
Ηράκλειτος (Heraclitus) ~535 - 475 BC

Jet quenching probes in small systems

(CMS Collaboration) JHEP 04 (2017) 039



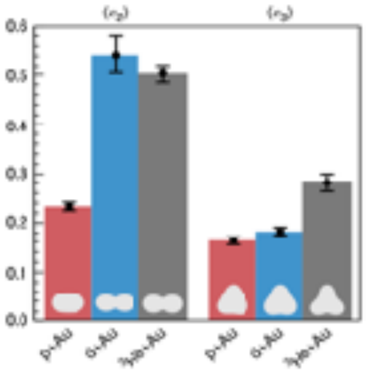
(Alice Collaboration) Phys.Rev. C91 (2015)

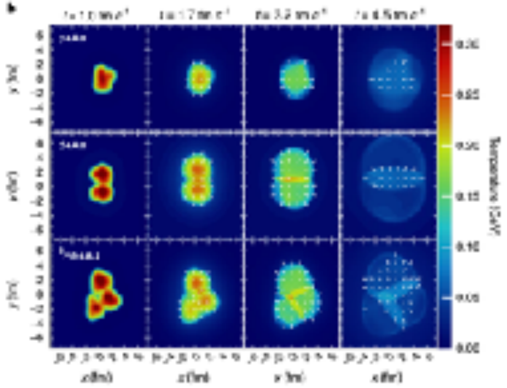


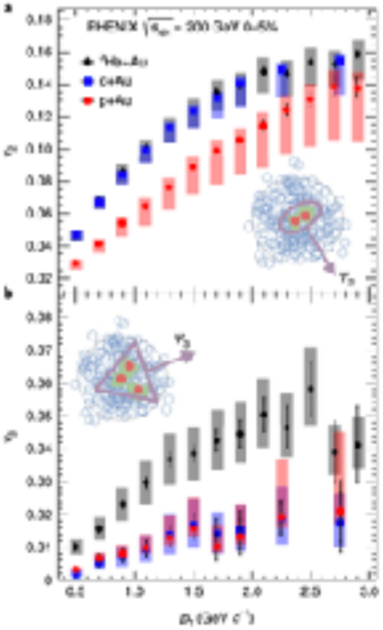
- R_{pPb} for min. bias collisions consistent with unity above ~2GeV/*c* → suppression is Pb-Pb is not a cold nuclear matter effect
- “centrality” dependence of R_{pPb} (i.e. Q_{pPb} defined to take into account biases from the multiplicity selection) is also consistent with 1

Probing different initial geometries

- Hydrodynamical models → initial geometry vs IS momentum correlation models
- Explore different initial collision geometry in p-Au, d-Au and He[3]-Au





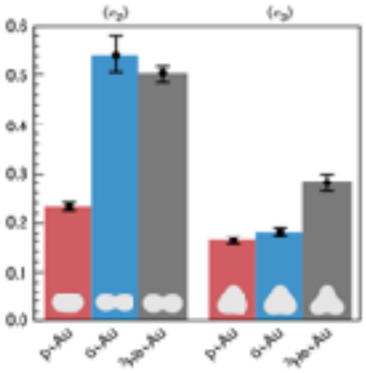


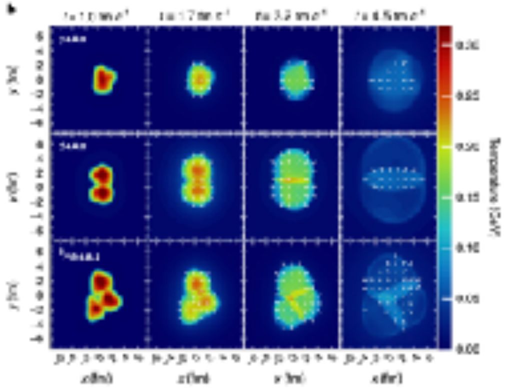
- Smaller $\langle \varepsilon_2 \rangle$ in p-Au → smaller v_2
- Larger $\langle \varepsilon_3 \rangle$ in He[3]-Au → smaller v_3
- What do the models have to say?

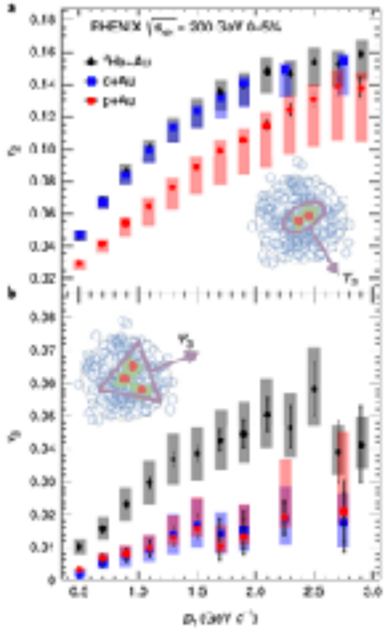
Probing different initial geometries

- Hydrodynamical models → initial geometry vs IS momentum correlation models
- Explore different initial collision geometry in p-Au, d-Au and He^3-Au

(PHENIX Collaboration), Nature Phys. 15, 214 (2019)



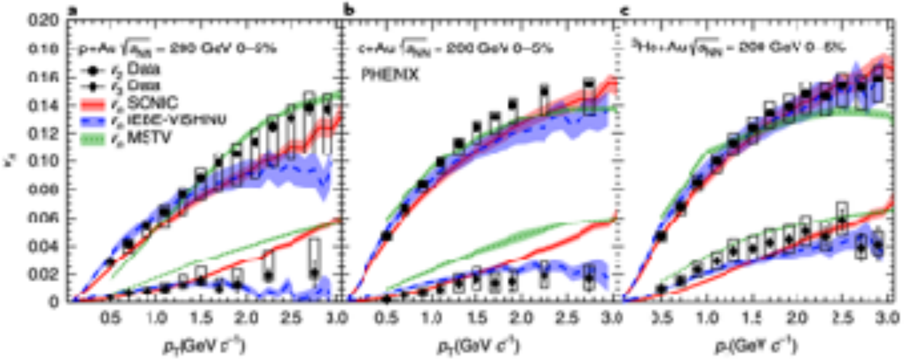


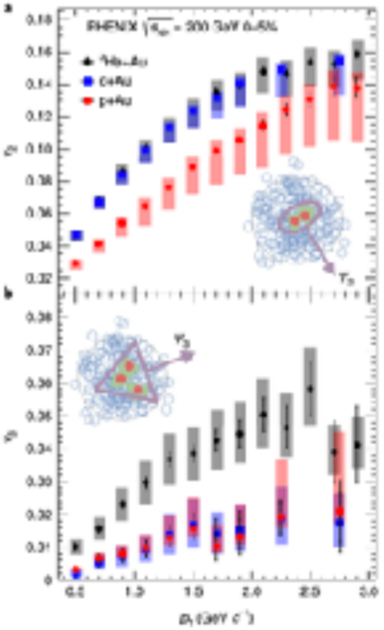


- Smaller $\langle \varepsilon_2 \rangle$ in p-Au → smaller v_2
- Larger $\langle \varepsilon_3 \rangle$ in He^3-Au → smaller v_3
- What do the models have to say?

Probing different initial geometries

- Hydrodynamical models → initial geometry vs IS momentum correlation models
- Explore different initial collision geometry in p-Au, d-Au and He^3-Au

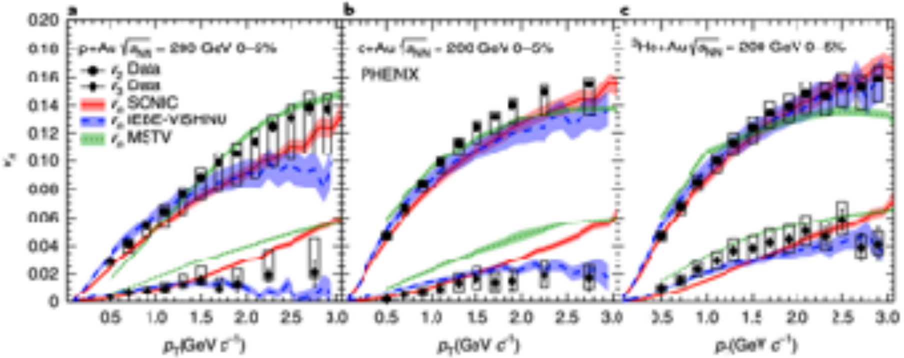




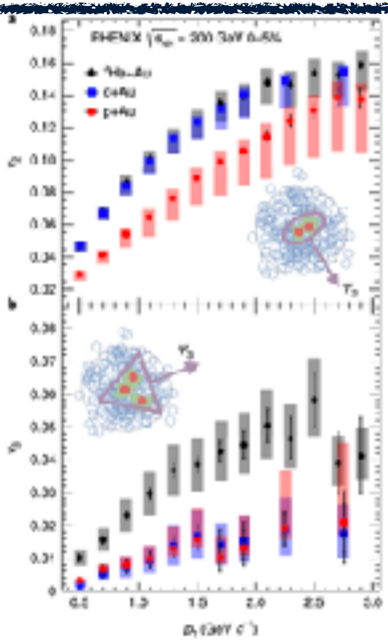
- Smaller $\langle \varepsilon_2 \rangle$ in p-Au → smaller v_2
- Larger $\langle \varepsilon_3 \rangle$ in He^3-Au → smaller v_3
- What do the models have to say?

Probing different initial geometries

- Hydrodynamical models → initial geometry vs IS momentum correlation models
- Explore different initial collision geometry in p-Au, d-Au and He^3-Au



(PHENIX Collaboration), Nature Phys. 15, 214 (2019)

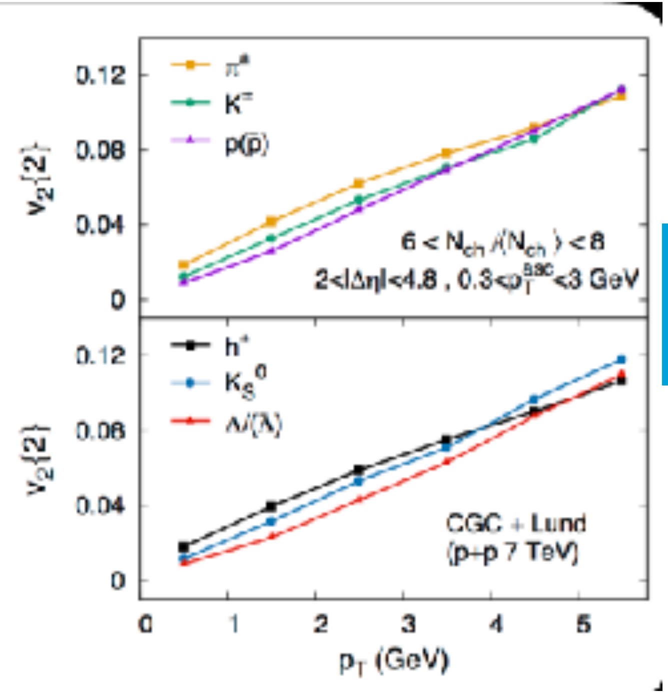


- Smaller $\langle \varepsilon_2 \rangle$ in p-Au → smaller v_2
- Larger $\langle \varepsilon_3 \rangle$ in He^3-Au → smaller v_3
- What do the models have to say?

Described well by models incorporating final state interactions

Mass ordering is not enough!!!

B. Schenke *et al.*, Phys. Rev. Lett. 117, 162301 (2016)

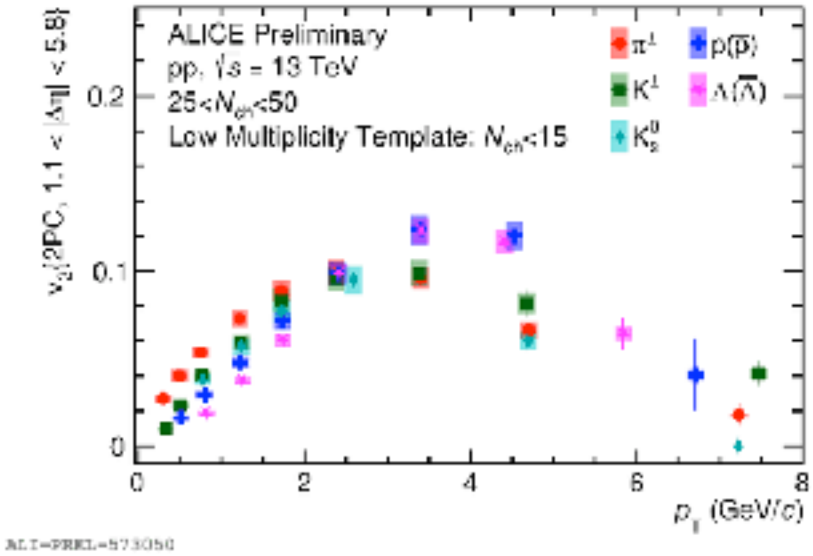


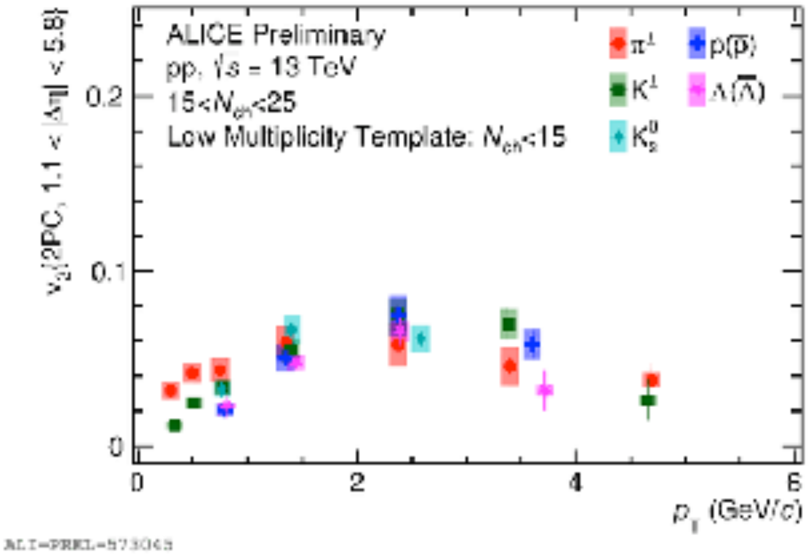
Yang-Mills initial state + Lund fragmentation does too

Emission from a common boosted source

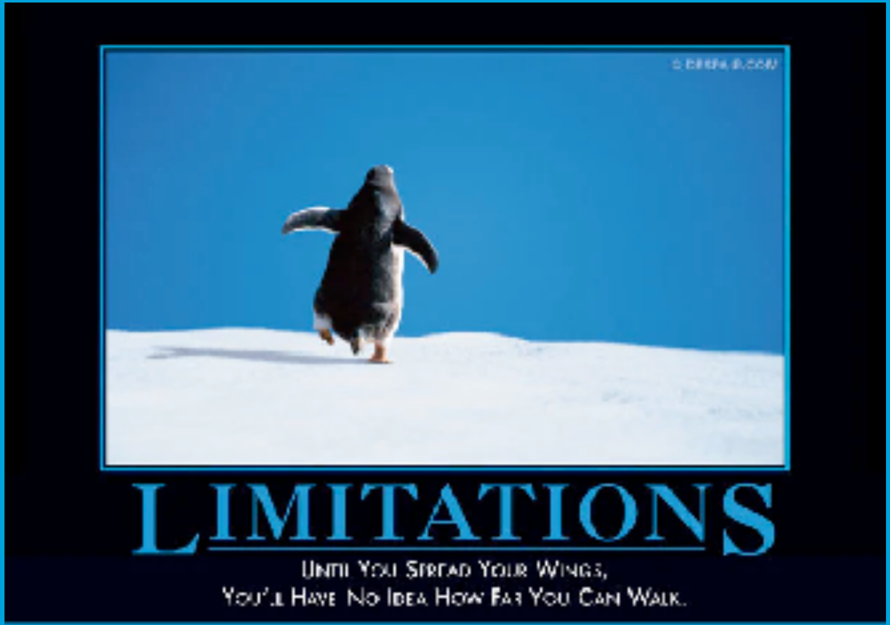
Identified particle v_2: intermediate p_T

Wenya Wu @ SQM2024



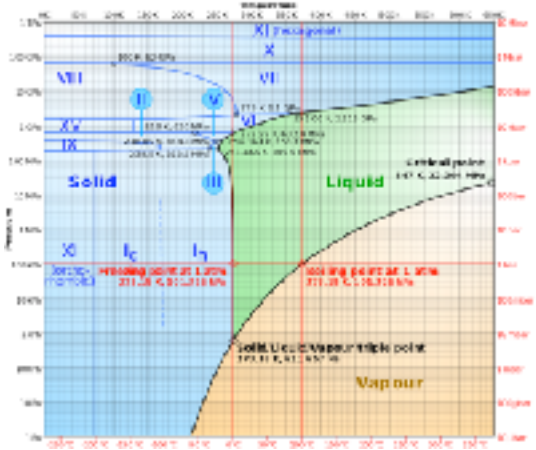


A glimpse in the near future



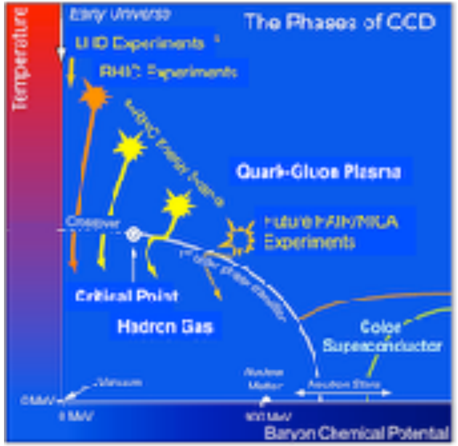
Mapping the QCD phase diagram

Phase diagram of water



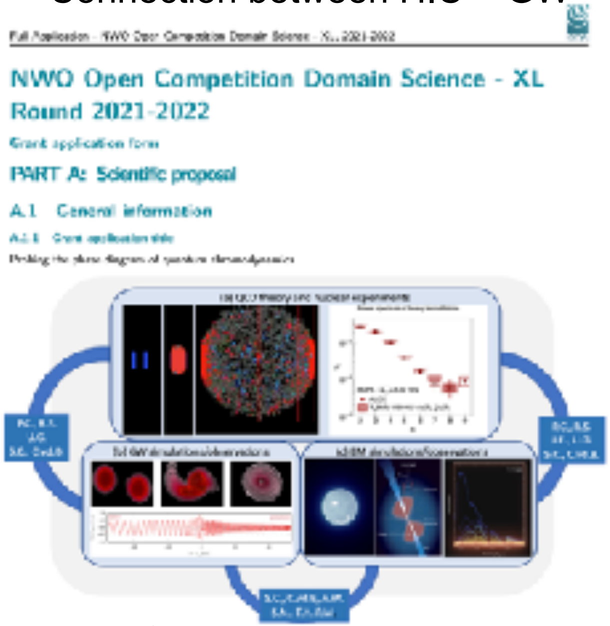
- Molecular interactions known to great detail
  - Different phases of water, including critical points extensively studied

(A version of the) QCD phase diagram



- What are the different phases of QCD?
  - Is there a critical point? Order of transitions?

Connection between HIC + GW

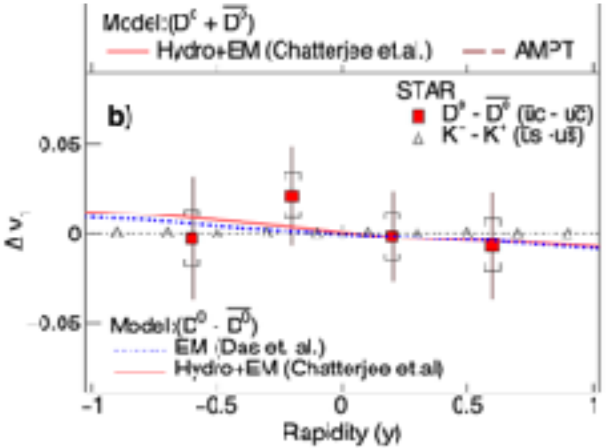


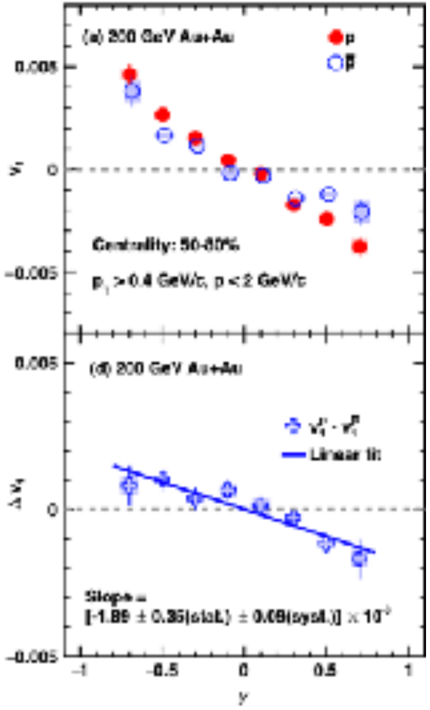
- Scientific consortium @ UvA, UU, RUG, UM
  - Connection through theoretical tools e.g. magneto-hydrodynamics

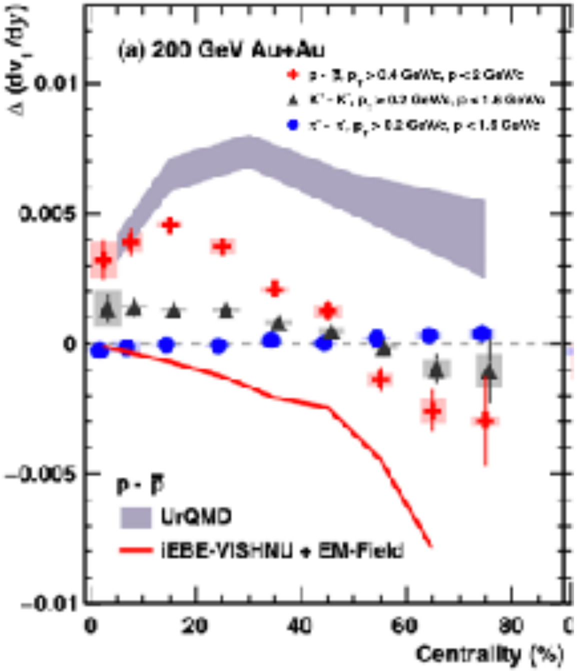
E/M fields: charge dependent v_n

(STAR Collaboration), Phys. Rev. Lett. 122, 162301 (2019)

(STAR Collaboration), Phys.Rev.X 14 (2024) 1, 011028





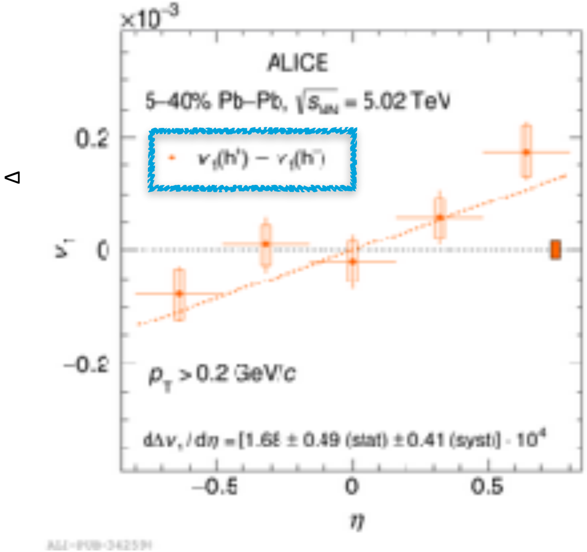


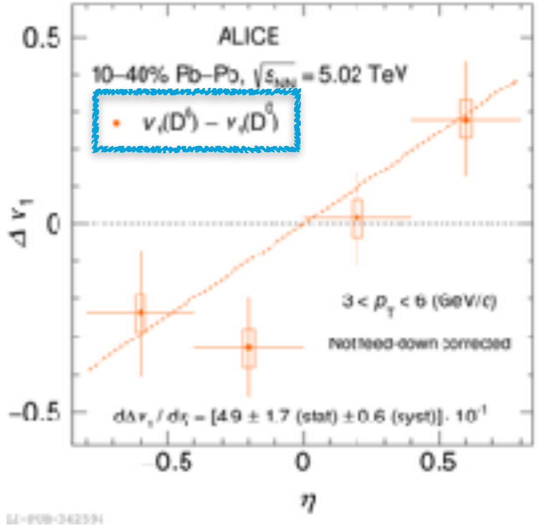
First experimental evidence for the existence of the early stage E/M fields

E/M fields: charge dependent v_n

(ALICE Collaboration), Phys. Rev. Lett. 125, 022301 (2020)

Small formation time → more sensitive probe of the early E/M fields





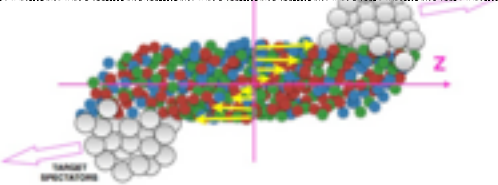
$\Delta v_1 \neq 0$ with a 2.6σ significance

$\Delta v_1 \neq 0$ with a 2.7σ significance

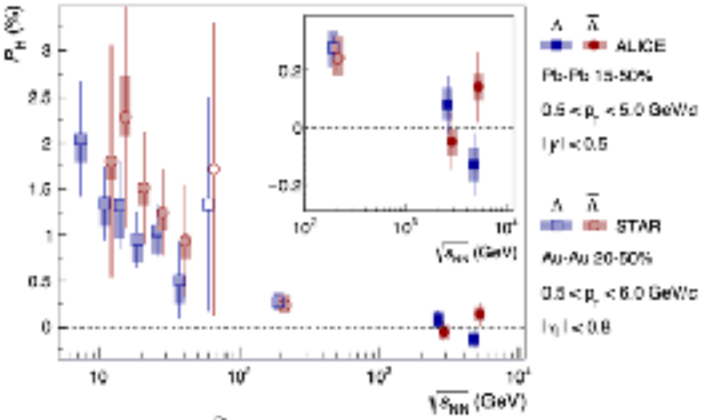
Significant progress expected with the upcoming Run3 data @ LHC

Experimental probe: global polarisation

F. Becattini *et al.*, Phys. Rev. C77, (2008) 024906



(STAR Collaboration) Nature 548, 62 (2017)
(ALICE Collaboration), Phys. Rev. C101 (2020) 044611



$$P_H = \frac{8}{\pi \alpha_H} \langle \sin(\Psi_{RP} - \varphi_p) \rangle$$

Large values of magnetic field and angular momentum at the initial stage of a HI collision

Part of L remains in the overlap region → rotating QGP

QGP exhibits vortical structure affected by the local velocity field

Spin proportional to magnetic moment

- Particles tend to be polarised along the initial angular momentum of the QGP
- Opposite effect for particles and antiparticles

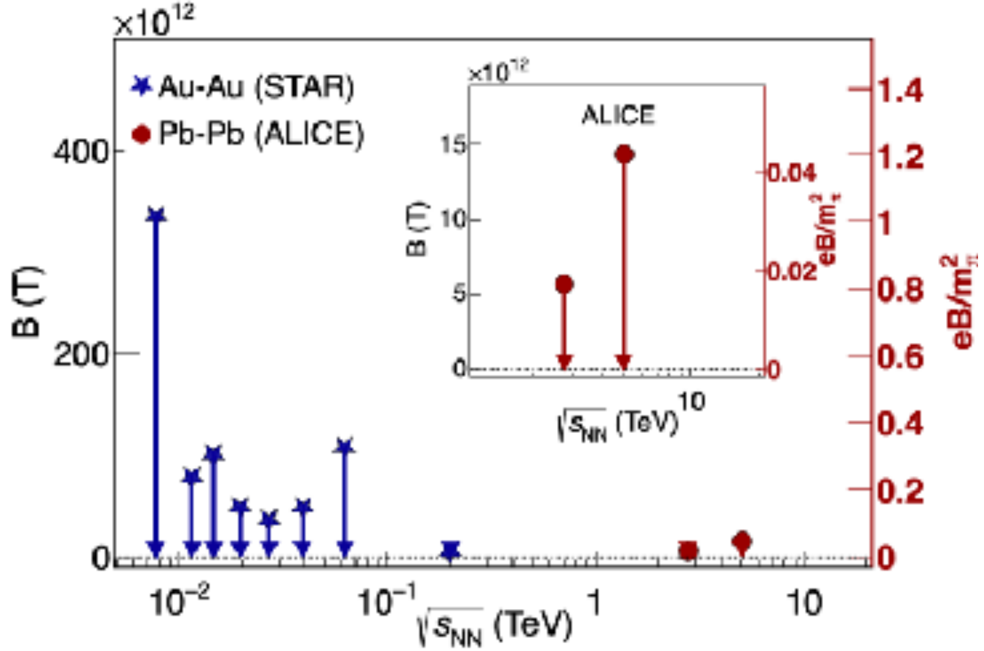
$$P_q^B \approx \mu_q \frac{B}{T} = \frac{Q_q}{2m_q} \frac{B}{T}$$

$$P_\Lambda \simeq \frac{1}{2}\frac{\omega}{T} + \mu_\Lambda \frac{B}{T}$$

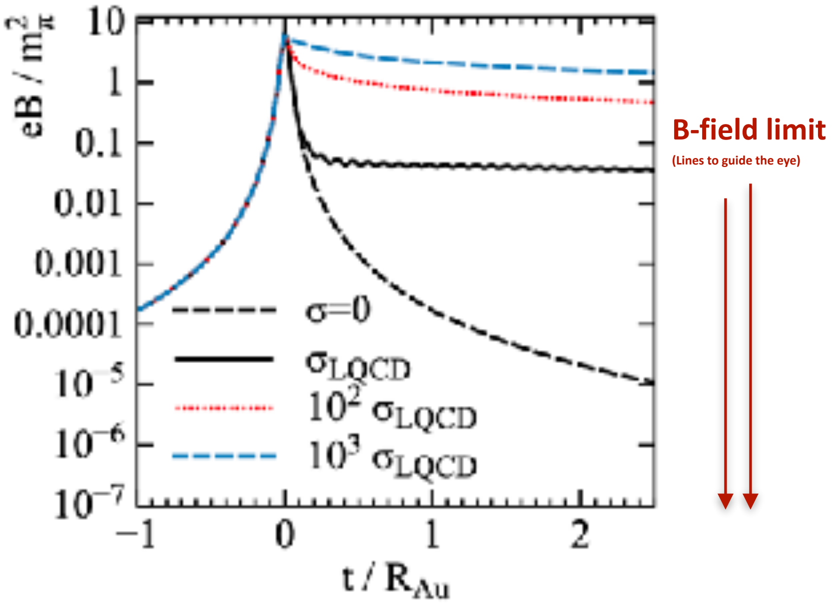
$$P_{\bar{\Lambda}} \simeq \frac{1}{2}\frac{\omega}{T} - \mu_\Lambda \frac{B}{T}$$

- Significant reduction of P_H at the LHC energies relative to RHIC
- No significant difference between Λ and anti-Λ ➞ (still) not sensitive to effects due to magnetic field

Experimental constrains on B

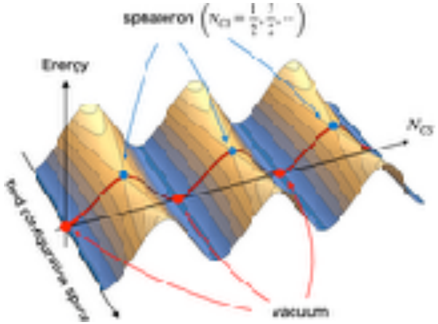


L. McLerran, V. Skokov, Nucl. Phys. *A* 929 (2014) 184



Current measurements provide tight constrains on the value of B at freeze out

Chiral anomalies in heavy ion collisions

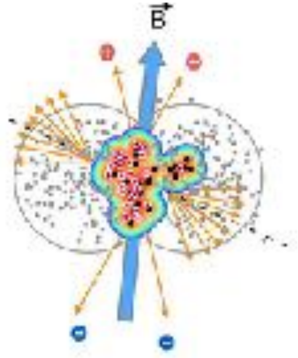


Chirality imbalance

$$\mu_5 = N_L - N_R$$

Anomalous transport

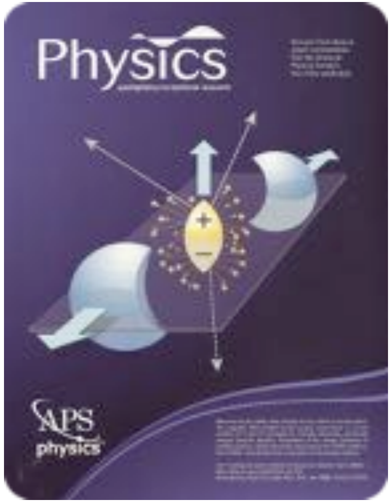
$$J = \frac{e^2}{2\pi^2}\mu_5 B$$



Magnetic field

$$B \approx \gamma Z e \frac{b}{R^3} \qquad \gamma = \frac{\sqrt{s_{NN}}}{2m_p}$$

Chiral Magnetic Effect (CME)



D. Kharzeev *et al.*, Phys. Rev. Lett. **81**, (1998) 512
D. Kharzeev, Phys. Lett. B **633**, (2006) 260
D. Kharzeev, Prog. Part. Nucl. Phys. **75** (2014) 133

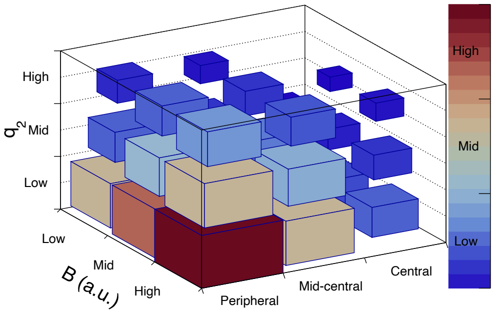
A possible new direction for run3+4

P. Christakoglou, EPJC (2024) 84:290

- Study a 2D plane that probes the signal (~B) and constrains the background (~v_2)
  - Gauge the value of B from the energy deposited in the ZDC
    - Fluctuations within a given centrality
    - Look for quadratic dependence of Δγ on the proxy of B
  - Gauge the value of v2 by studying q_2 quantiles
    - Linear dependence on the background

$$\mu_5 = N_L - N_R$$

$$J = \frac{e^2}{2\pi^2}\mu_5 B$$

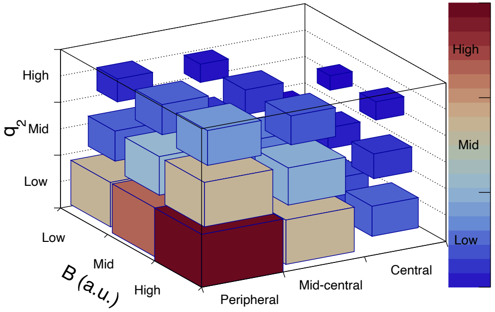


A possible new direction for run3+4

- Study a 2D plane that probes the signal (~B) and constrains the background (~v_2)
  - Gauge the value of B from the energy deposited in the ZDC
    - Fluctuations within a given centrality
    - Look for quadratic dependence of Δγ on the proxy of B
  - Gauge the value of v2 by studying q_2 quantiles
    - Linear dependence on the background

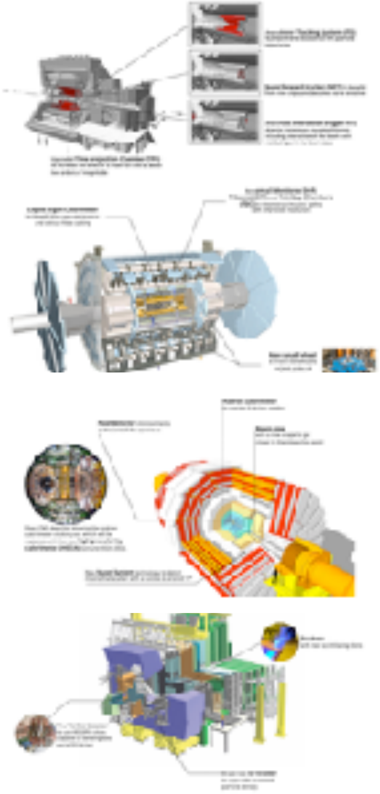
$$\mu_5 = N_L - N_R$$

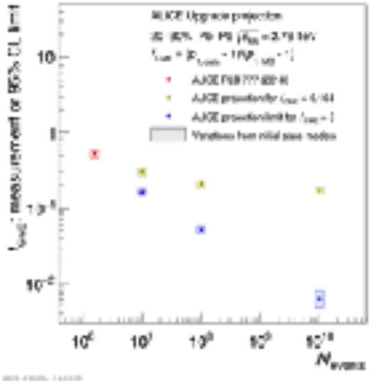
$$J = \frac{e^2}{2\pi^2}\mu_5 B$$



Future prospects

arXiv:1812.06772





- 2024-2025:10x AuAu MB data than the existing sample

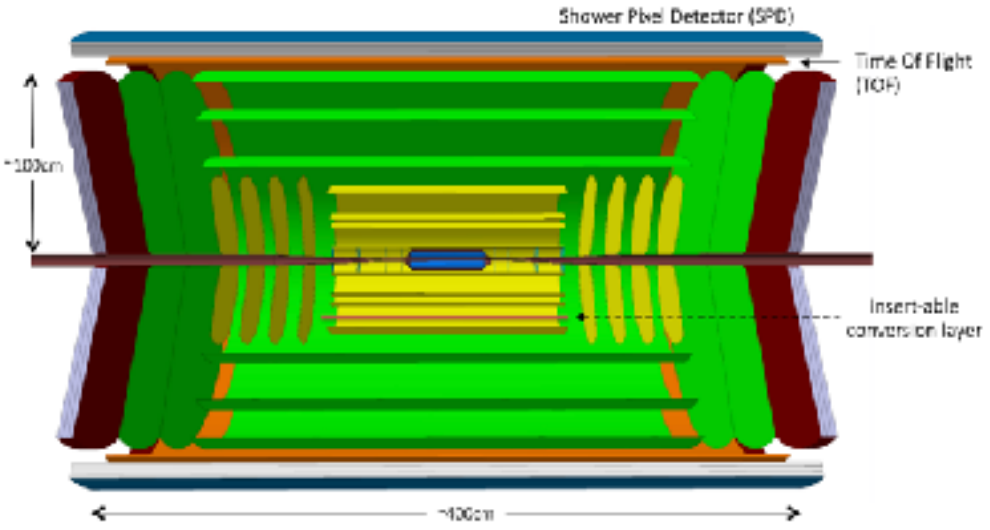
+Isobaric collisions @ LHC?

System	Year	$\sqrt{s_{NN}}$ (TeV)	L_{int}
Pb-Pb	2010, 2011	2.76	~75 μb^{-1}
Pb-Pb	2015, 2018	5.02	~0.8 nb^{-1} ~2 nb^{-1}
Pb-Pb	**2023-2032**	**5.5**	**~12 nb^{-1}**
Xe-Xe	2017	5.44	~0.3 nb^{-1}
p-Pb	2013, 2016	5.02	~18 nb^{-1} ~50 μb^{-1}
p-Pb	2016	8.16	~25 nb^{-1} ~186 nb^{-1}
p-Pb	**2023-2032**	**8.16**	**~0.6 pb^{-1}**
O-O	**2025**	**5.5**	**~500 μb^{-1}**

Looking at the future: HI@LHC 2032+

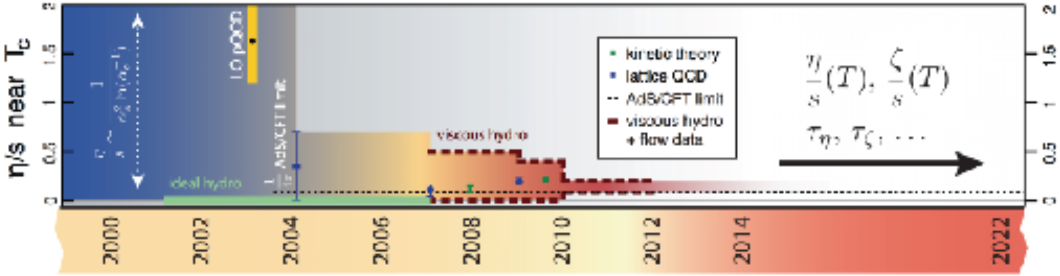
- Full azimuthal coverage with $|\eta| < 4$
- Retractable first layers inside the beam pipe
- Fast timing silicon detectors, TOF, RICH, muon detector
- Physics focus
  - (Multi-)heavy flavour states
  - Quarkonia states
  - Soft photons
  - Exotic states
  - Chiral symmetry restoration

https://arxiv.org/abs/1902.01211



A lot of progress…but still plenty of unanswered questions

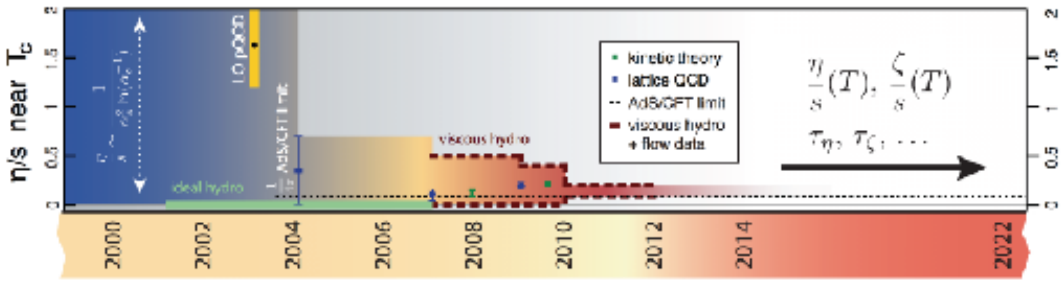
A lot of progress…but still plenty of unanswered questions

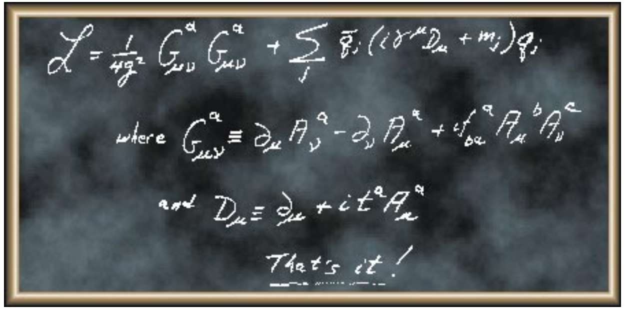


- Additional precision measurements (e.g. heavy quarks, jets) → knowledge of poorly constrained parameters
- New phenomena (e.g. vorticity, magnetic fields, CME, CMW…)
- How does hadronisation work?
- Origin of collectivity in small systems → can this lead to a unified picture of how QCD matter evolves as a function event activity?
- Critical point in QCD phase diagram?
- Connection with GW physics → how does QCD matter behave at large values of μ_B?

A lot of progress…but still plenty of unanswered questions

How does a strongly coupled QGP emerge from QCD?





- Additional precision measurements (e.g. heavy quarks, jets) → knowledge of poorly constrained parameters
- New phenomena (e.g. vorticity, magnetic fields, CME, CMW…)
- How does hadronisation work?
- Origin of collectivity in small systems → can this lead to a unified picture of how QCD matter evolves as a function event activity?
- Critical point in QCD phase diagram?
- Connection with GW physics → how does QCD matter behave at large values of μ_B?

Discover the proper microscopic picture that describes the macroscopic behaviour of the QGP

Thank you for your attention!

Panos.Christakoglou@maastrichtuniversity.nl

Backup