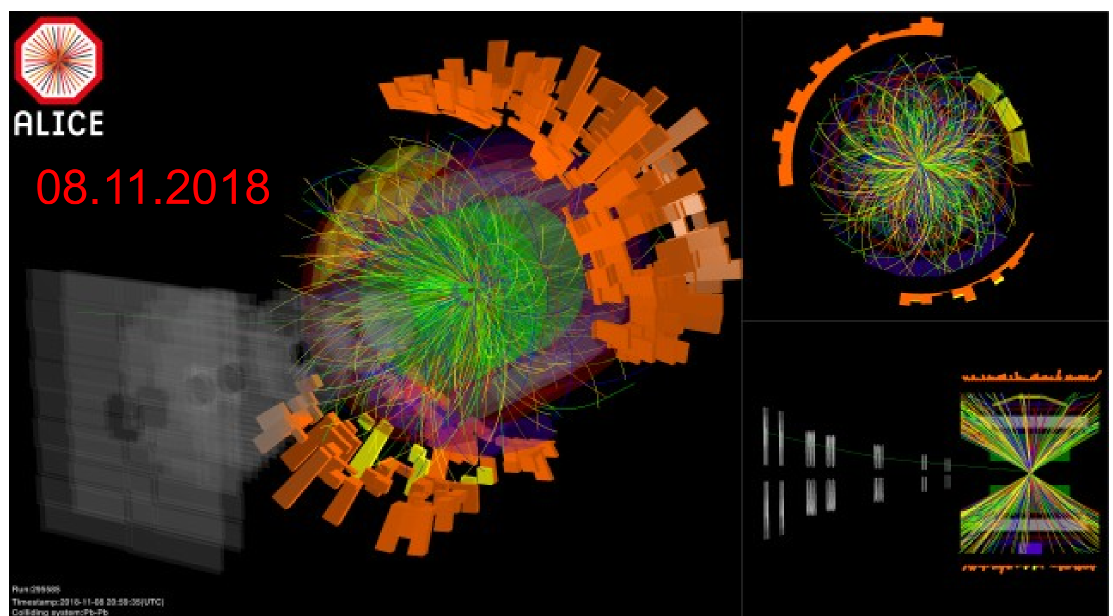
Probing the Quark Gluon Plasma with anisotropic flow measurements in ALICE

A. Dobrin (CERN & ISS)

for the ALICE Collaboration

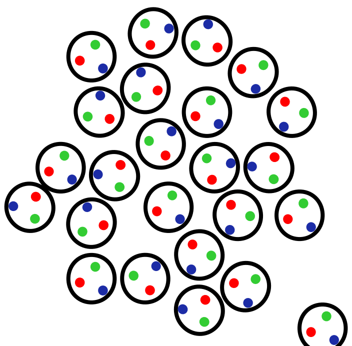
ALICE papers

Phys. Lett. B 784 (2018) 82
JHEP 07 (2018) 103
JHEP 09 (2018) 006
arXiv:1809.09371

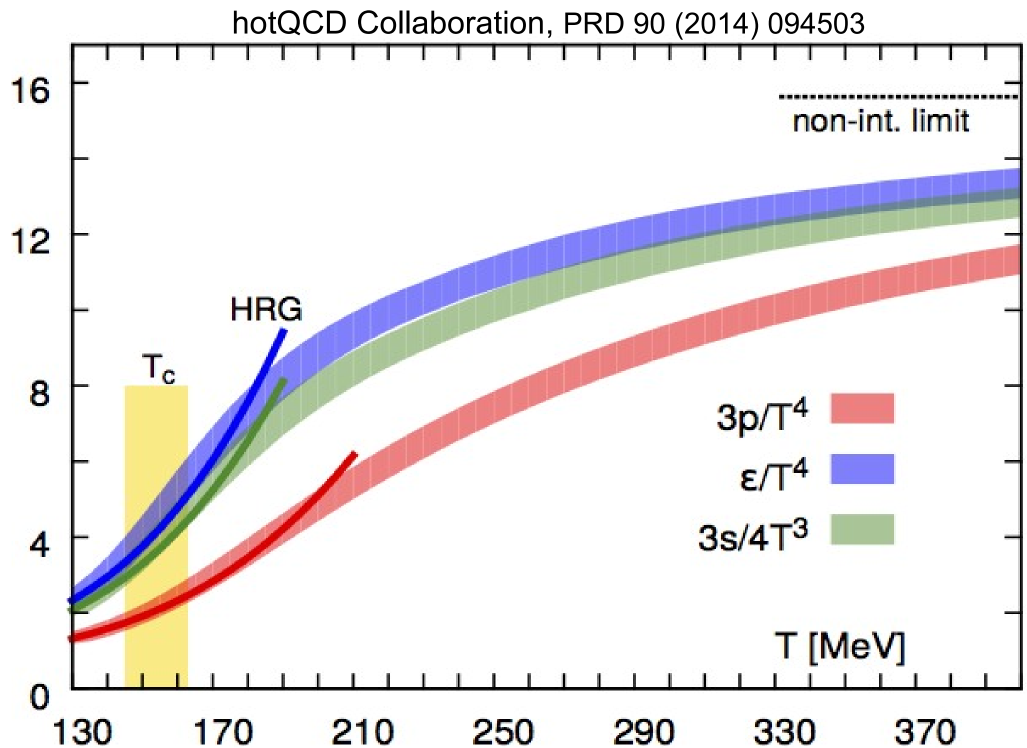


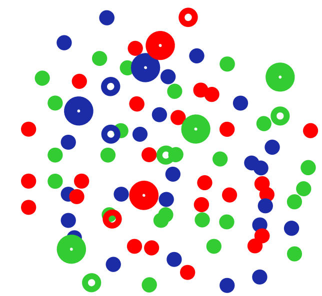
Introduction

Lattice QCD



Nuclear matter
(confined)





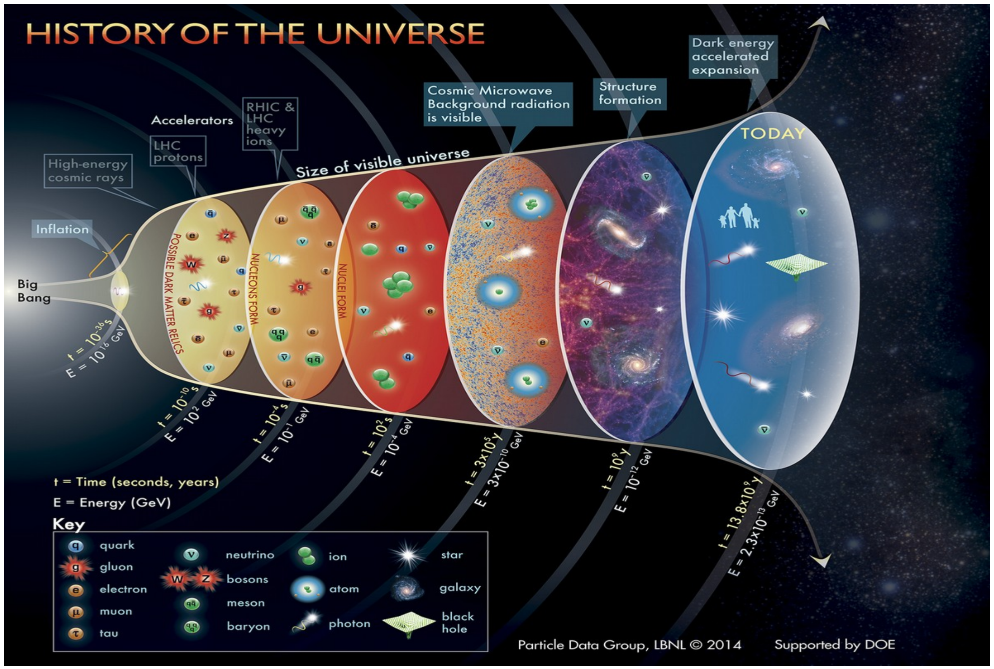
Quark Gluon Plasma
(deconfined)

$$p=\frac{1}{3}\varepsilon=g\frac{\pi^2}{90}T^4$$

$$\frac{\varepsilon}{T^4}=g\frac{\pi^2}{30}$$

- Present understanding of QCD:
  - Heating + compression → Quark Gluon Plasma (QGP): deconfined system of quarks and gluons
  - Lattice QCD: transition expected to occur at critical energy density ε_c~0.5 GeV/fm^3 and temperature T_c~156 MeV
    - Free quark gluon gas limit not reached → residual interactions

Why study QGP?



QGP might have existed in the expanding Universe in the first μs after the Big Bang

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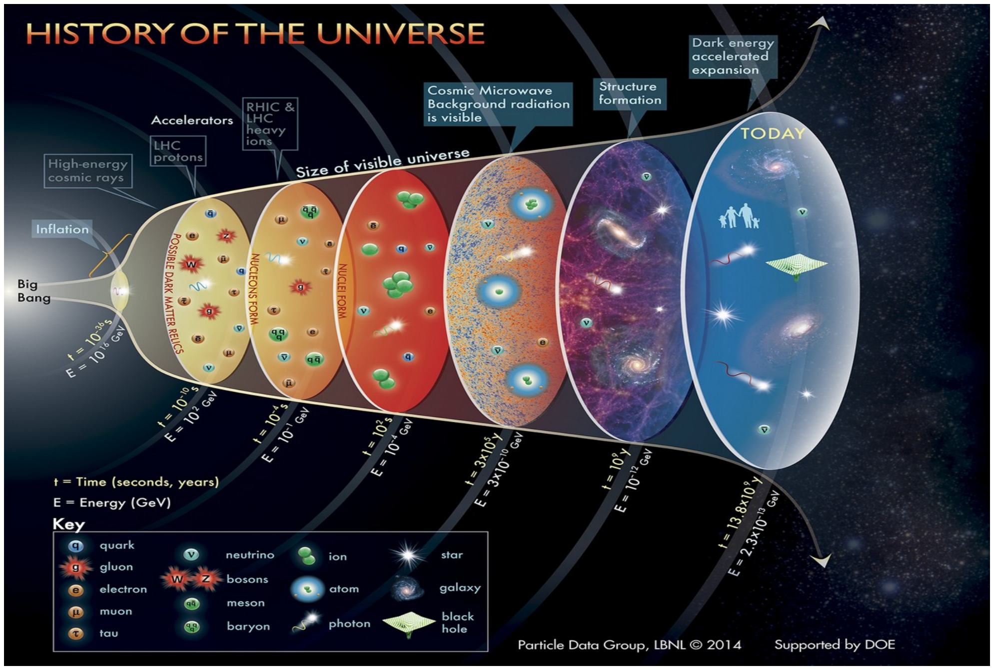

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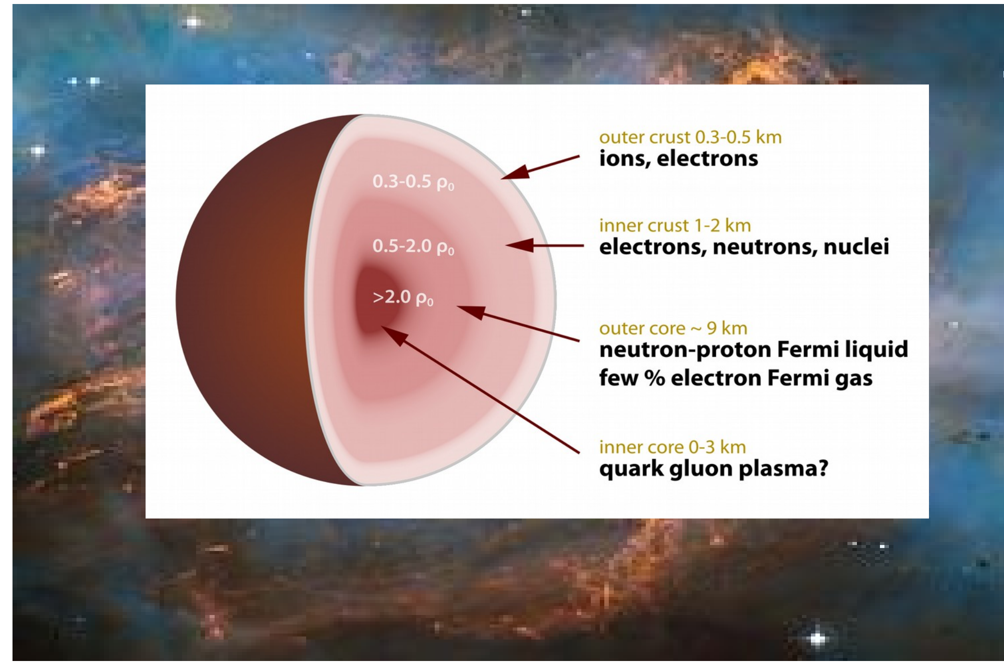
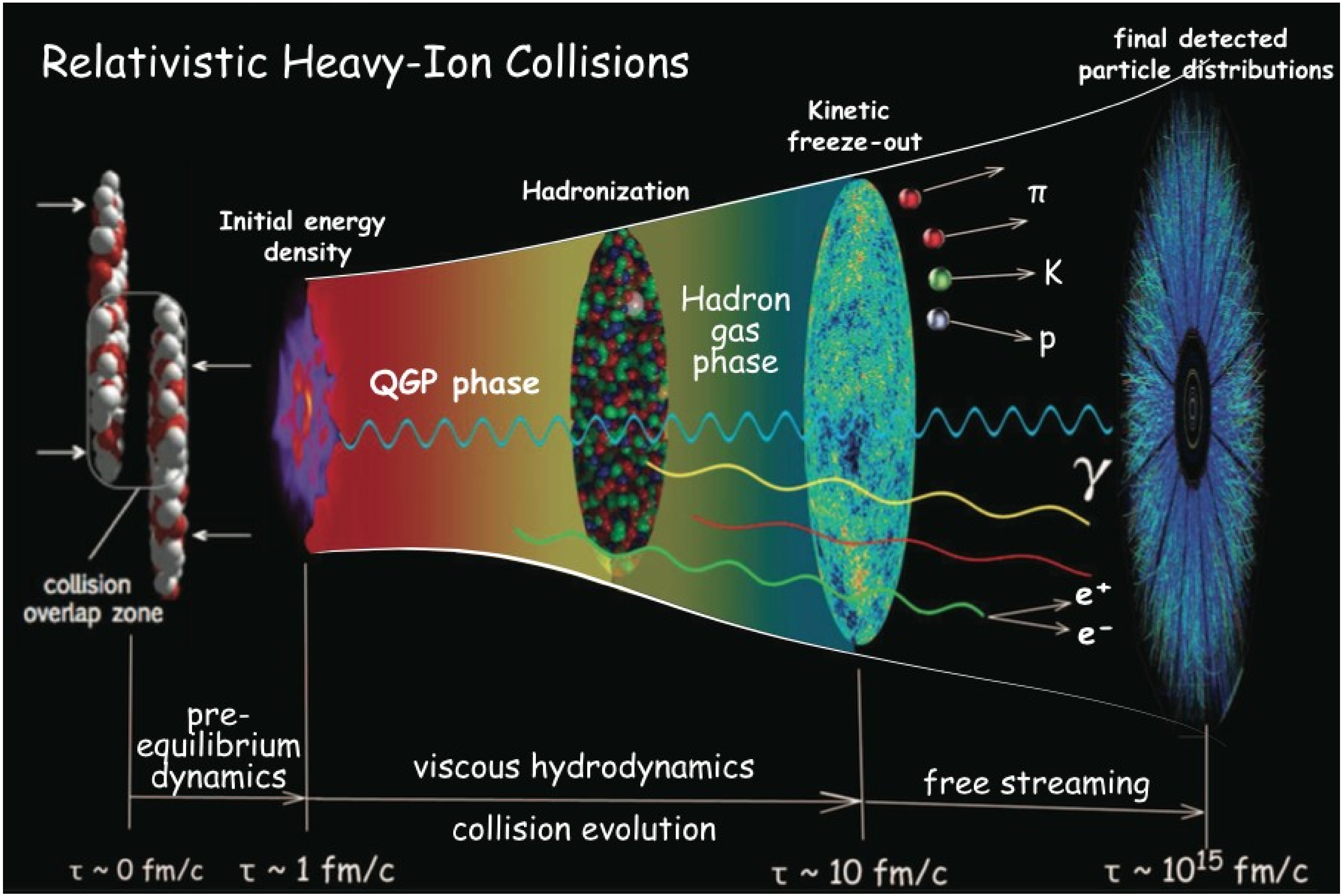


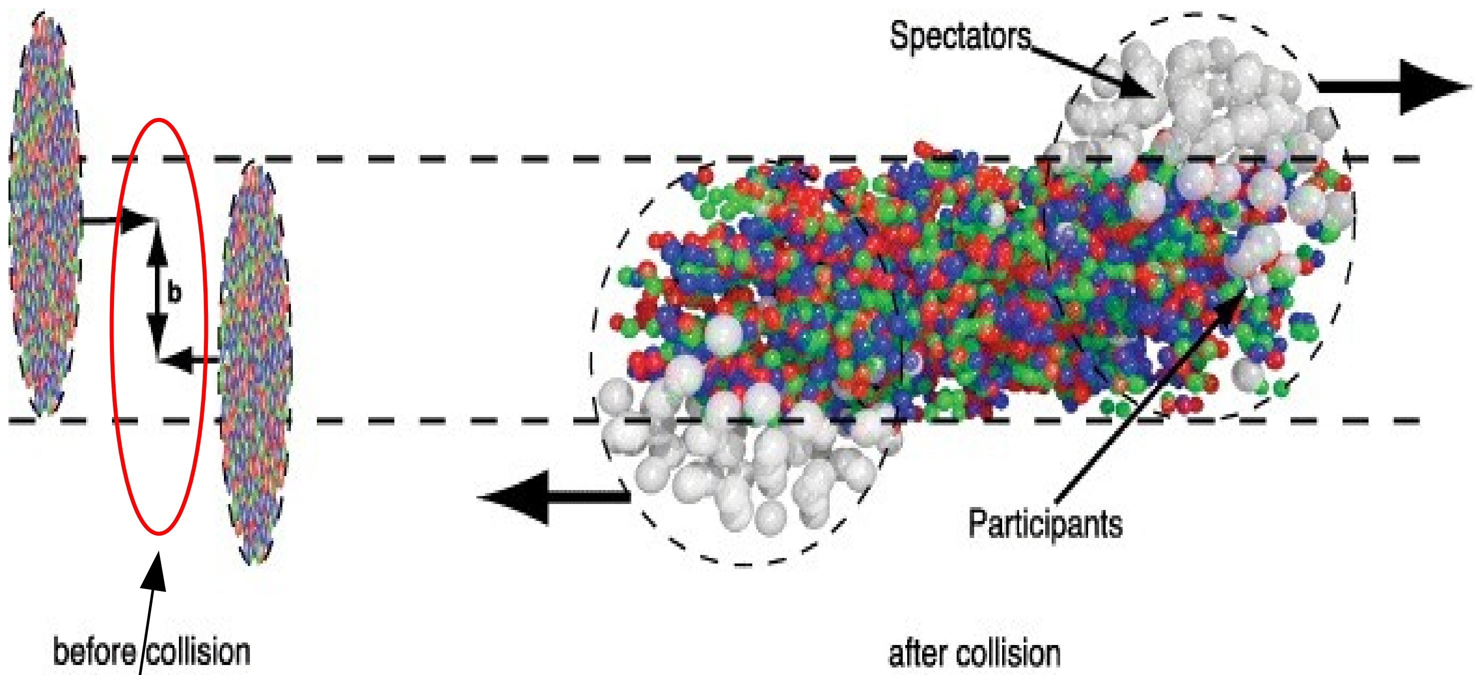
Neutron stars: a more likely place for QGP to exist → mass controlled by the equation of state (EoS) of nuclear matter

Time evolution of a heavy-ion collision



P. Sorensen / C. Shen

Centrality: controlling volume and shape



Impact parameter b

- Perpendicular to beam direction
- Connects centers of colliding nuclei
- Not measured directly → estimated by centrality

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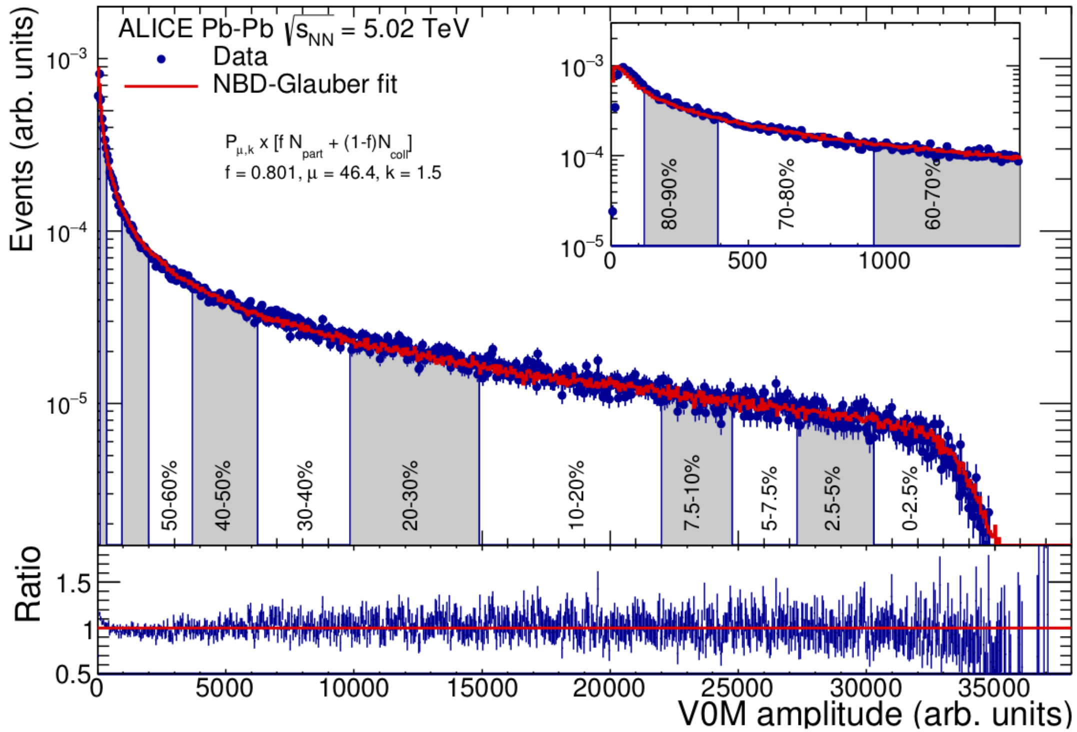
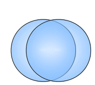
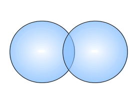
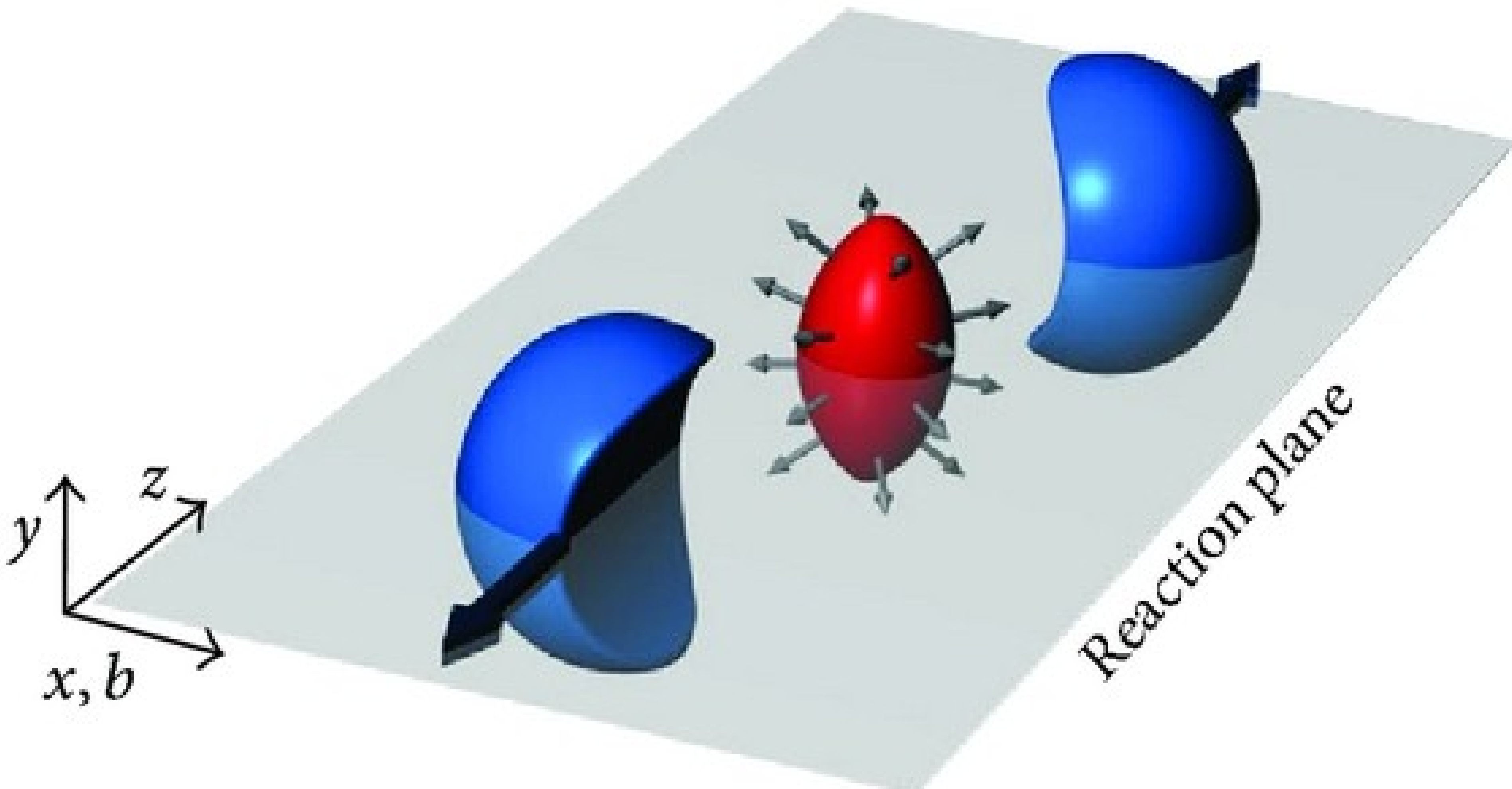


Impact parameter b

- Perpendicular to beam direction
- Connects centers of colliding nuclei
- Not measured directly → estimated by centrality
- Centrality determined from particle multiplicities
  - Most central: 0-5% centrality 
  - Peripheral: 70-80% centrality 

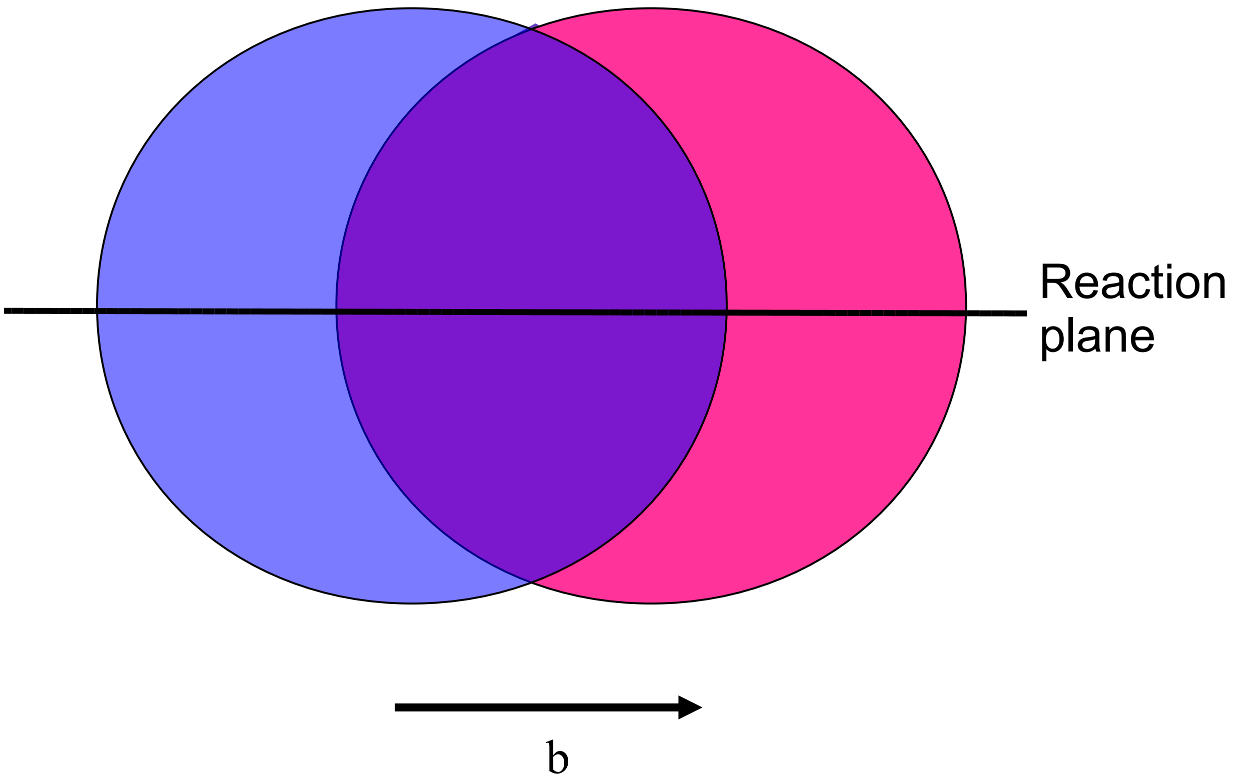
Anisotropic flow

Elliptic flow



Elliptic flow

Animation: Mike Lisa

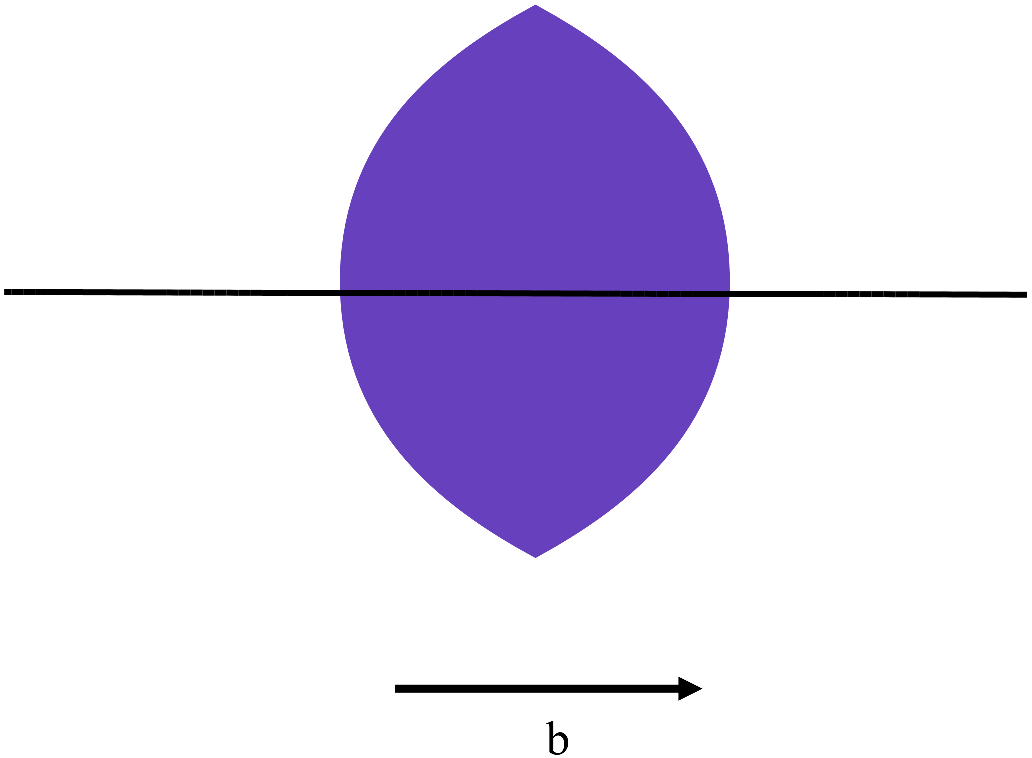


Elliptic flow

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

1) Superposition of independent pp

Animation: Mike Lisa



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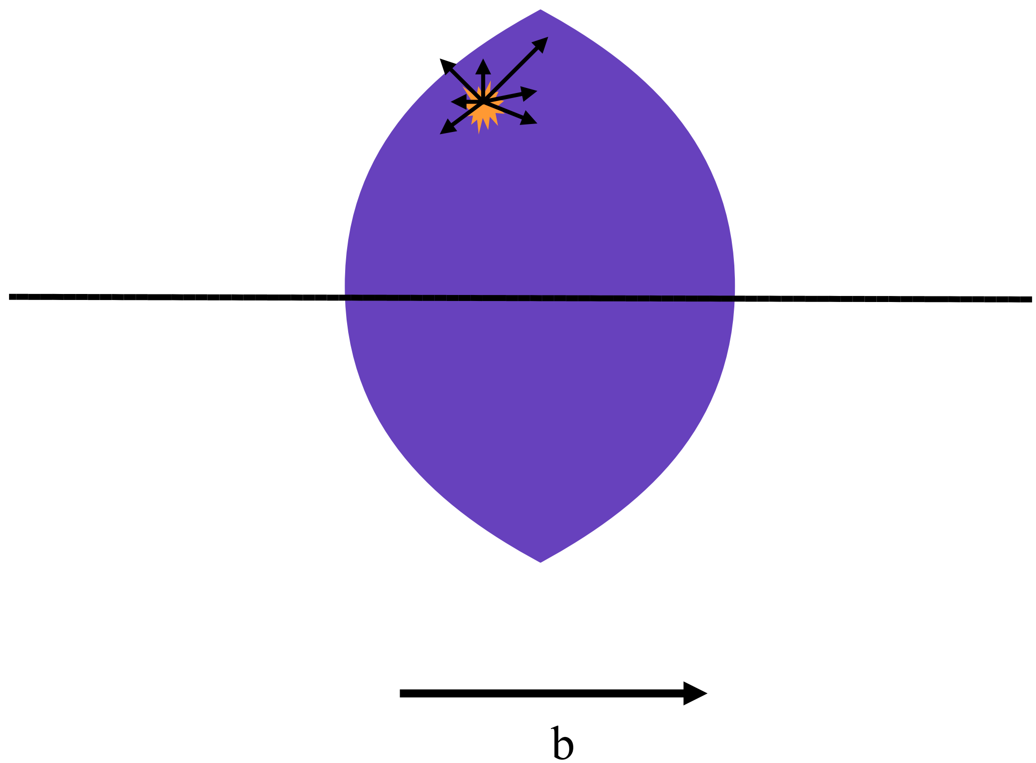

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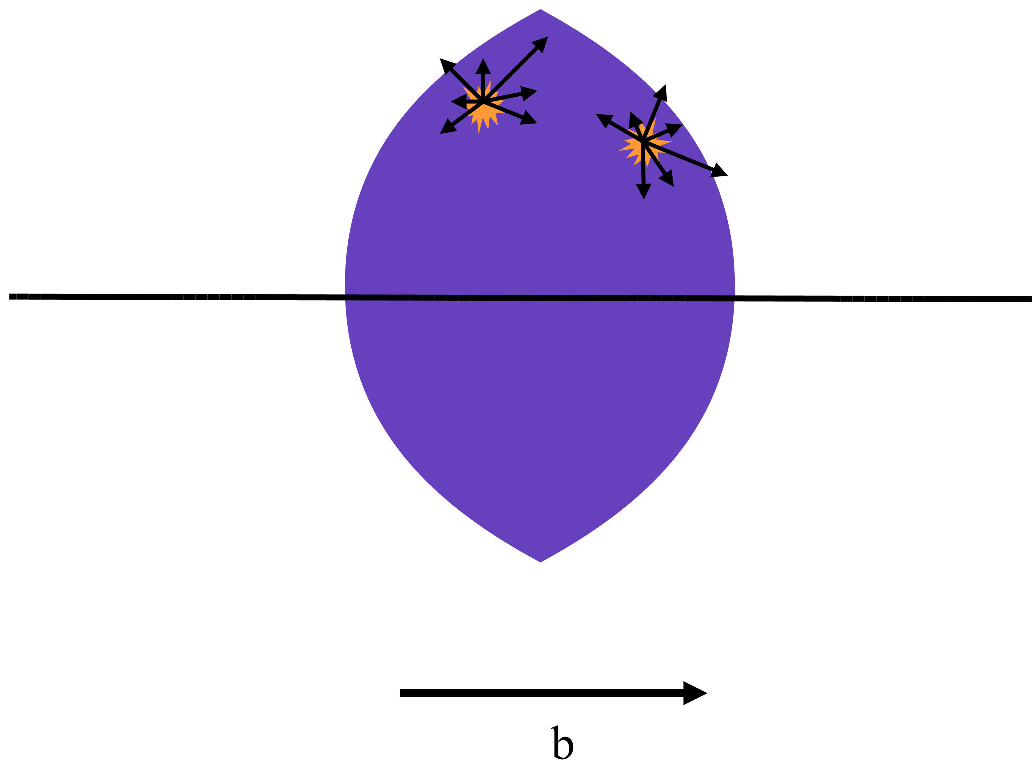

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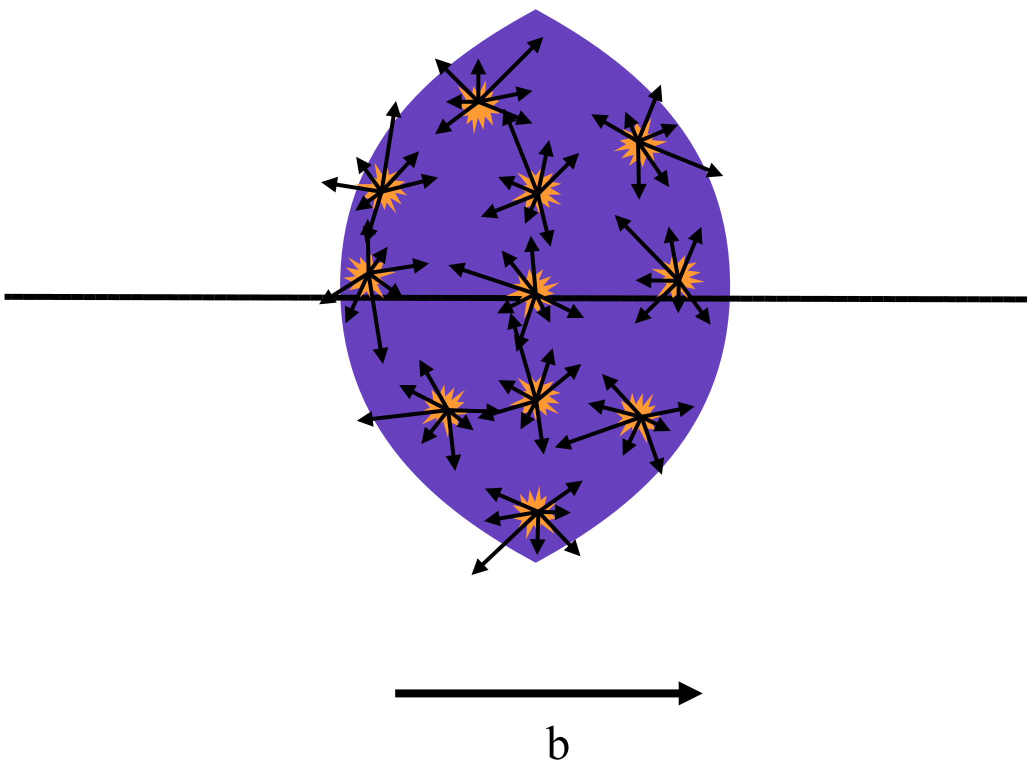

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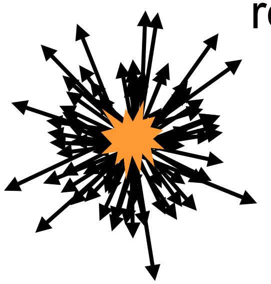

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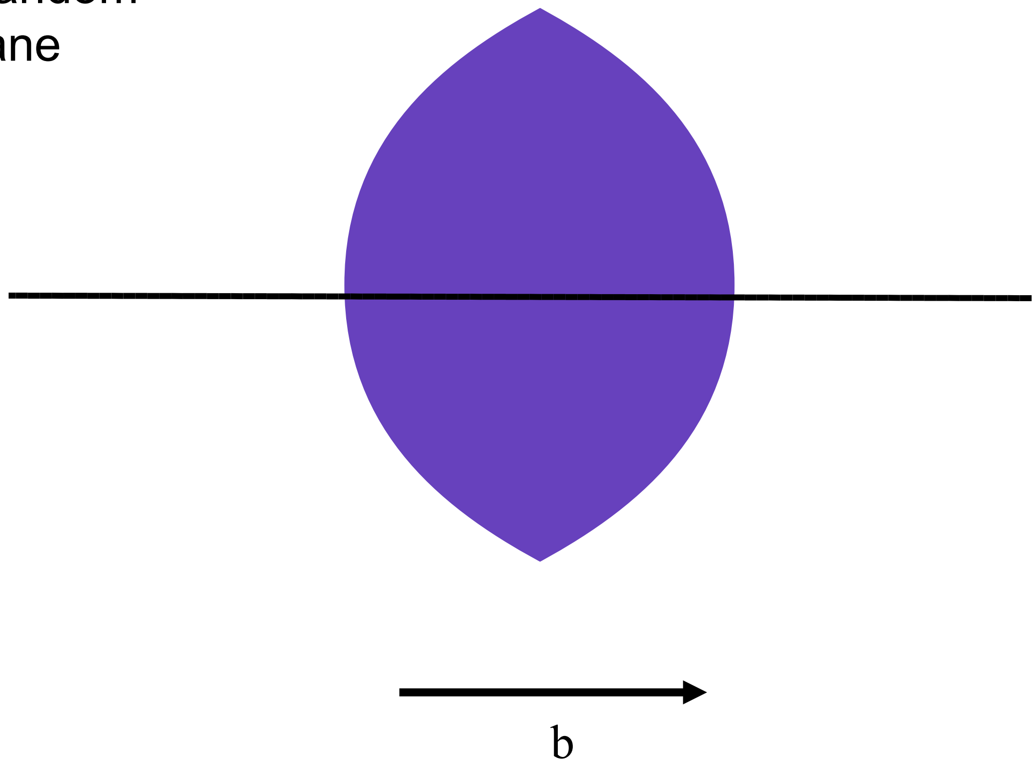

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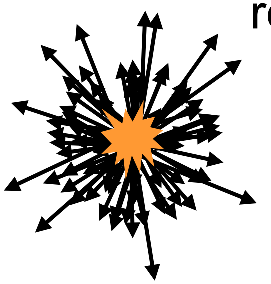

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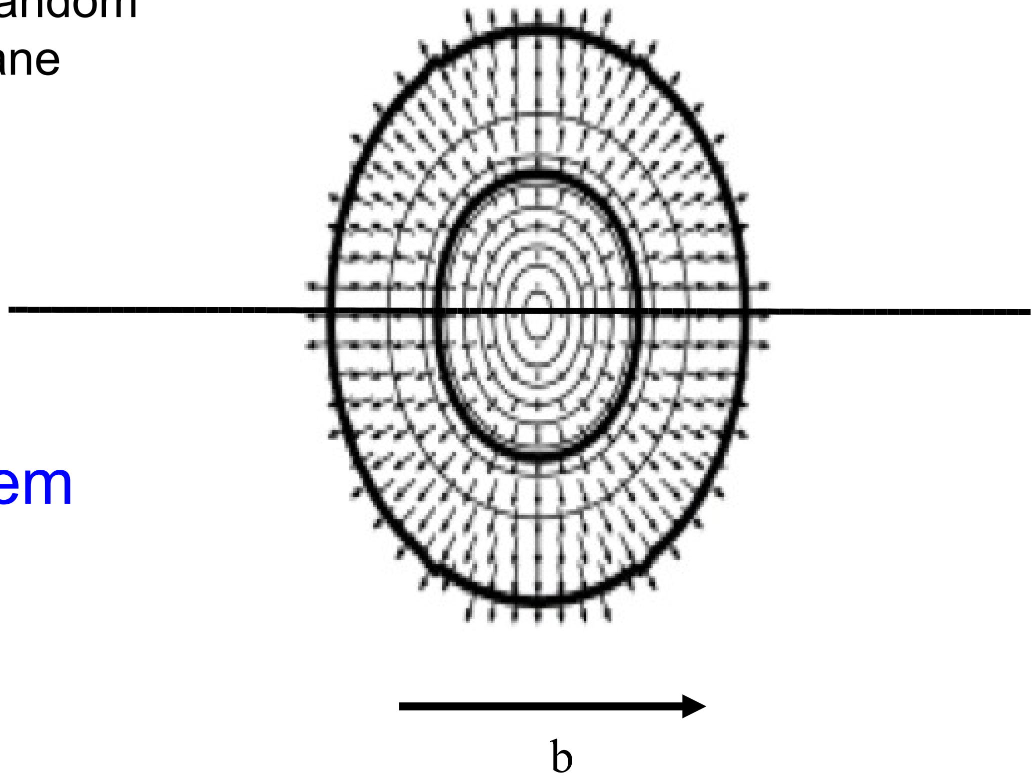

2) Evolution as a bulk system

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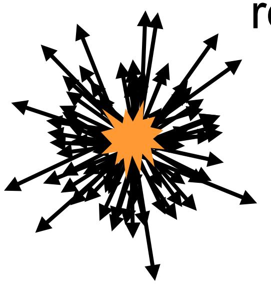

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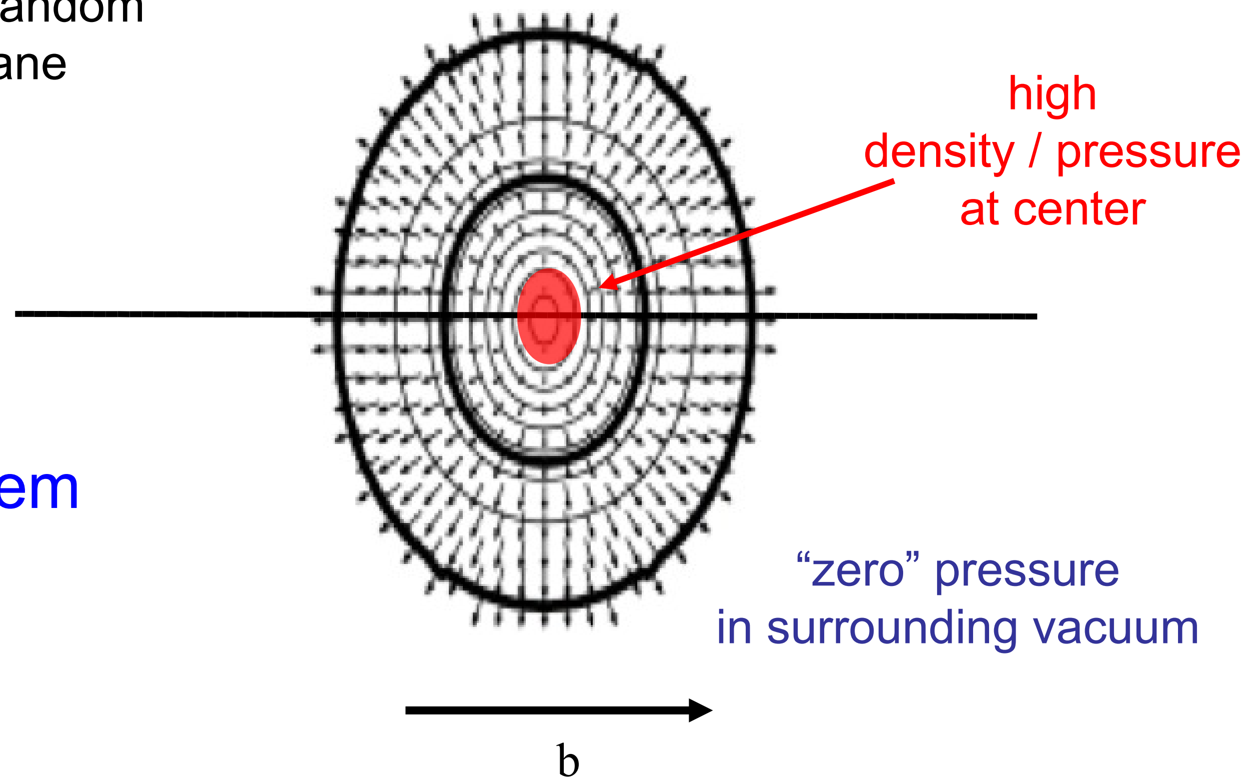

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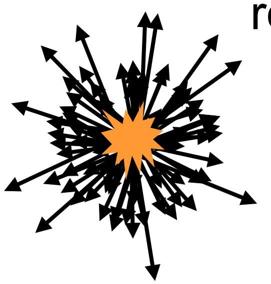

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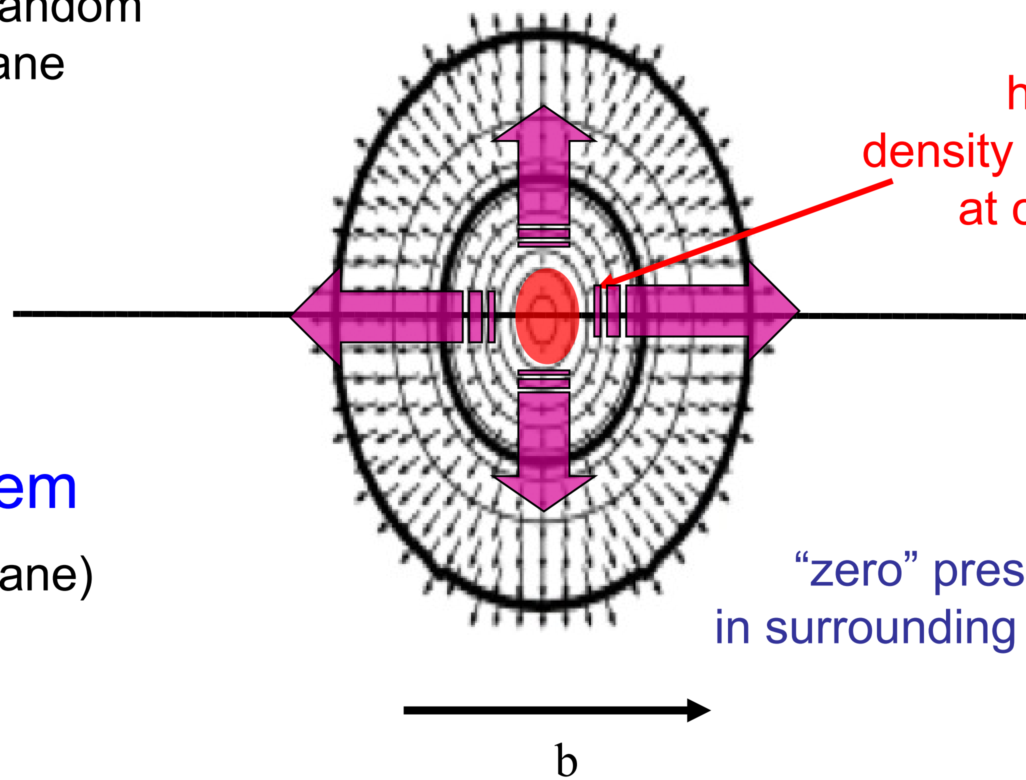

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Pressure gradients (larger in-plane) push bulk out → "flow"

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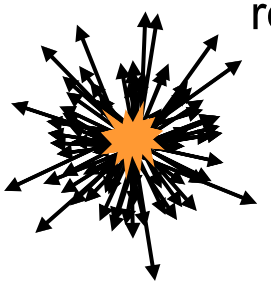

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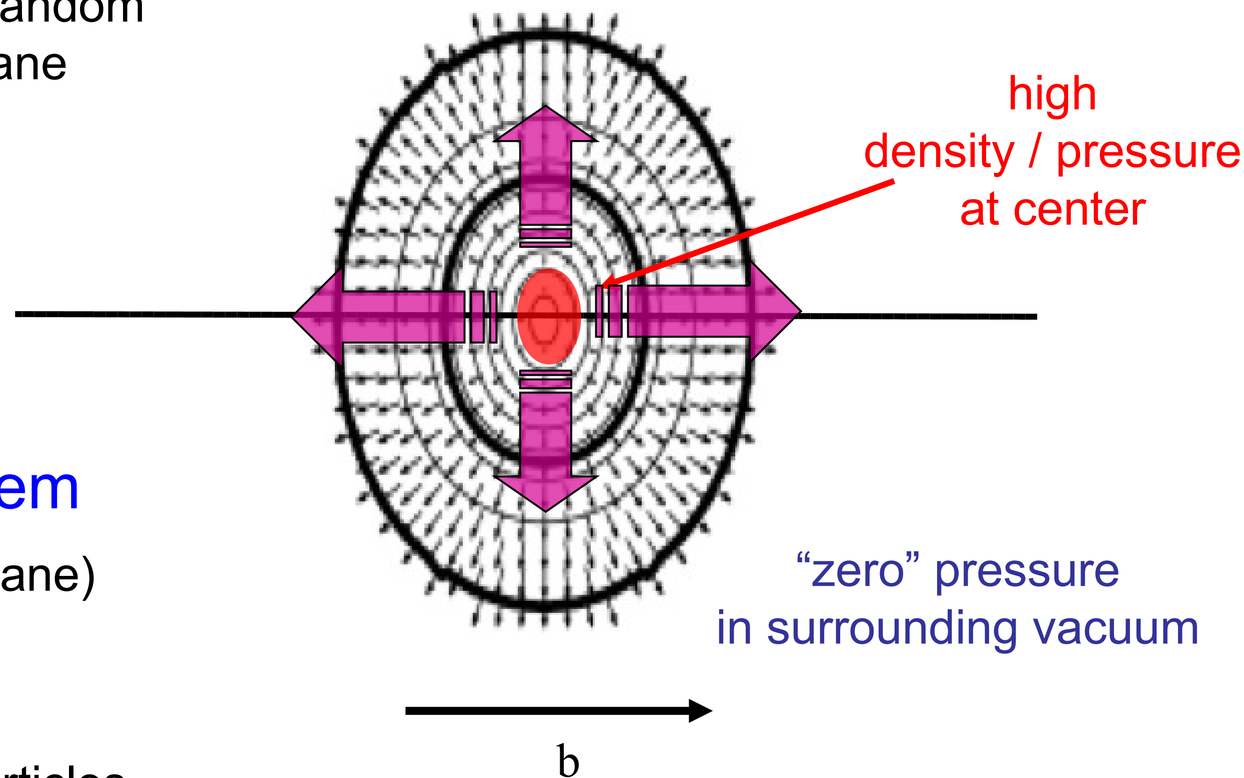

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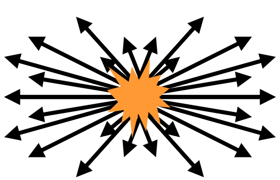

More, faster particles seen in-plane

Elliptic flow

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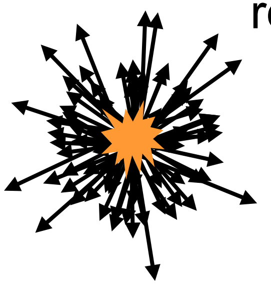

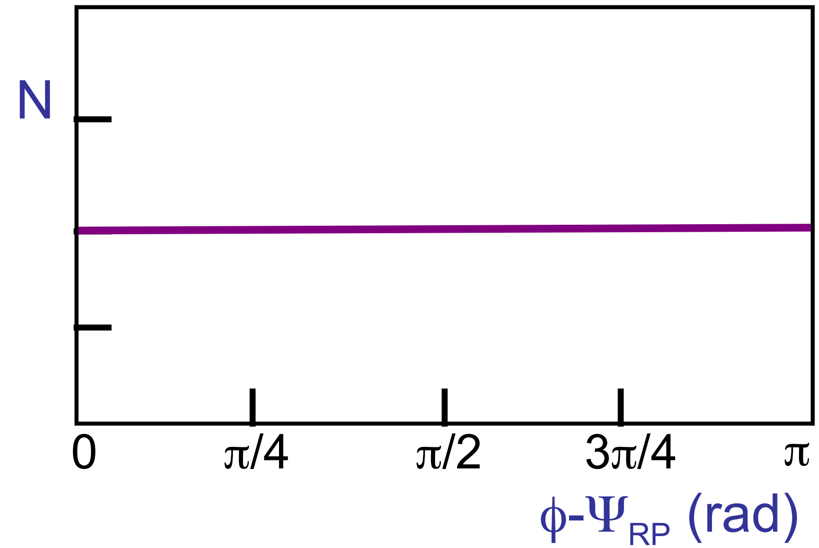

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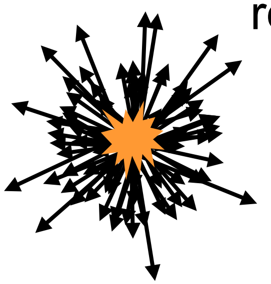

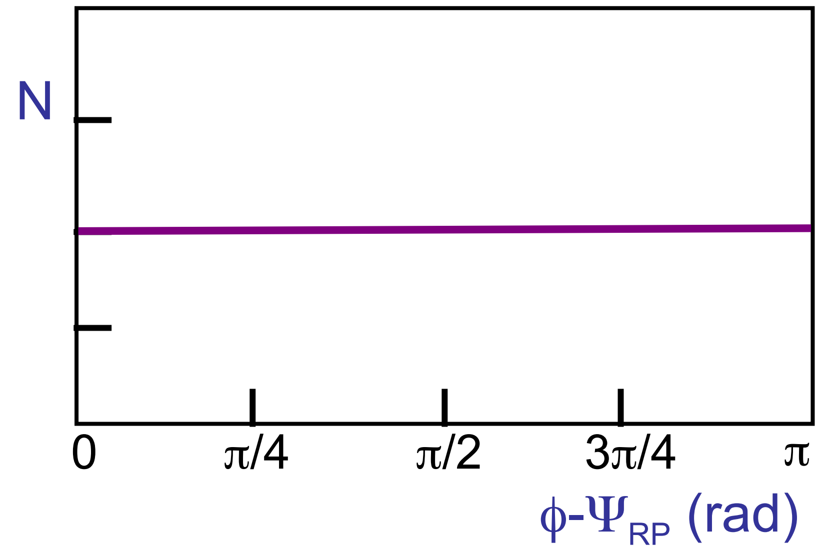

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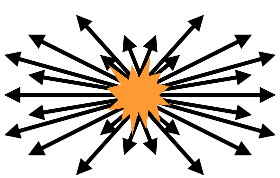
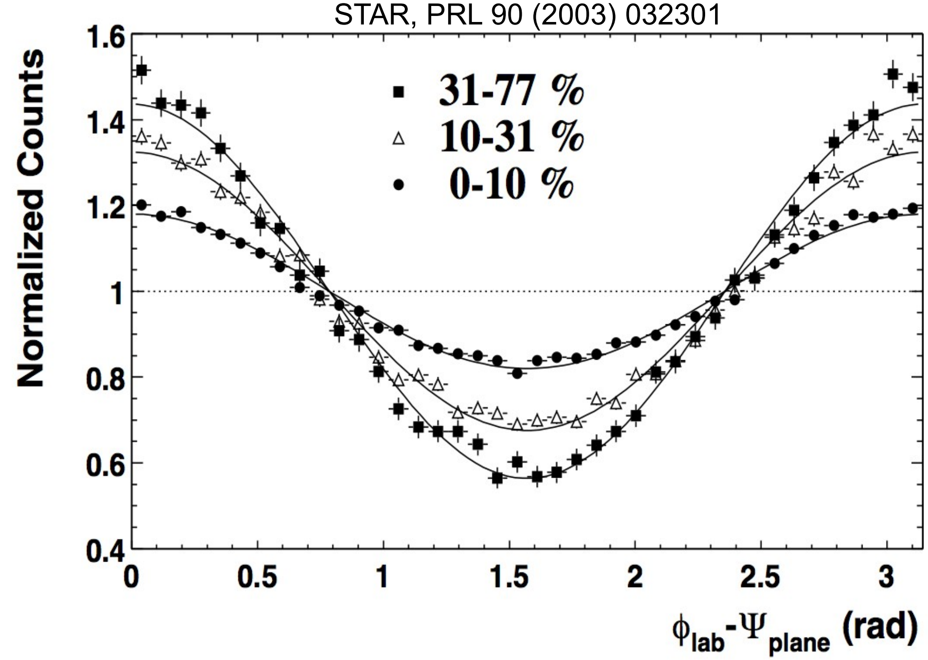
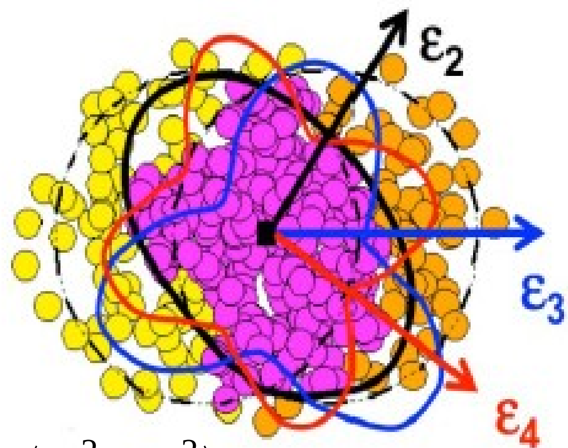


More, faster particles seen in-plane

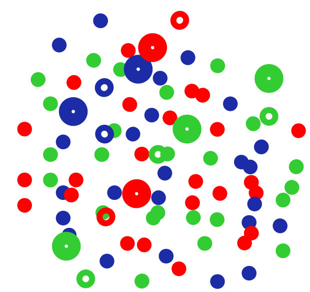
STAR, PRL 90 (2003) 032301

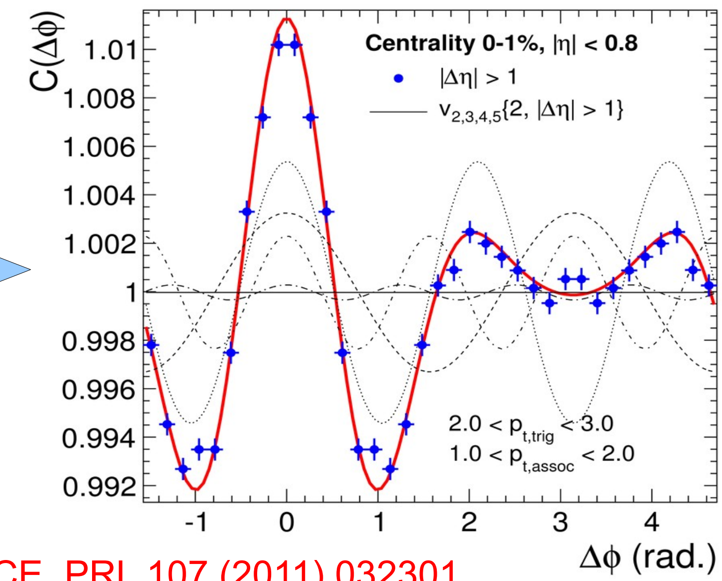


Anisotropic flow



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



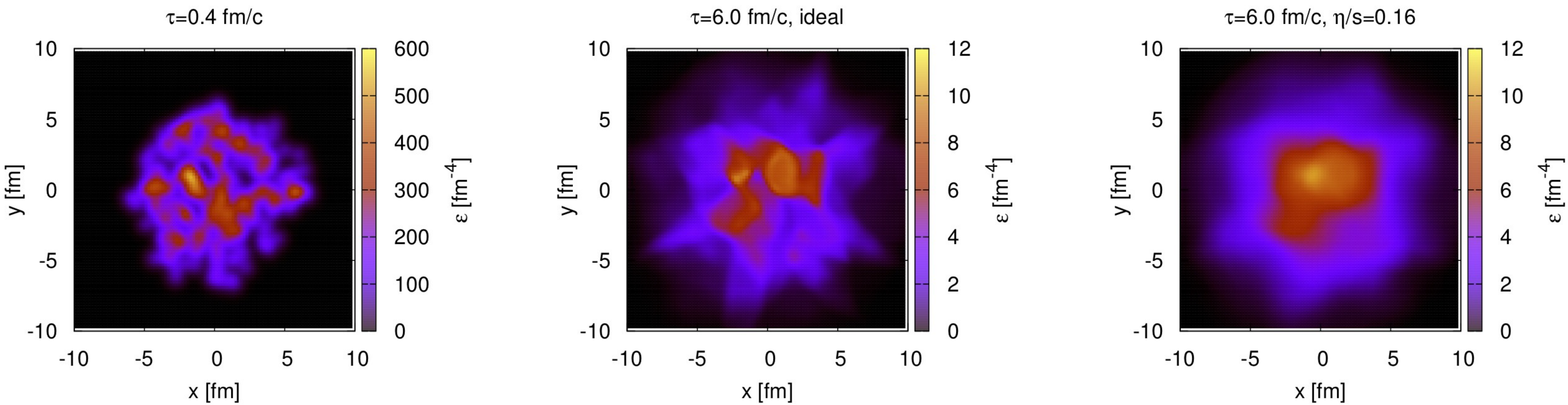


ALICE, PRL 107 (2011) 032301

- Most central collision: fluctuations of participating nucleons
  - Higher (odd) harmonics since $\Psi_{RP} \rightarrow \Psi_n$ (n-th order symmetry plane)
- Anisotropic flow: the transfer of initial spatial anisotropy into the final anisotropy in momentum space via collective interactions

Anisotropic flow

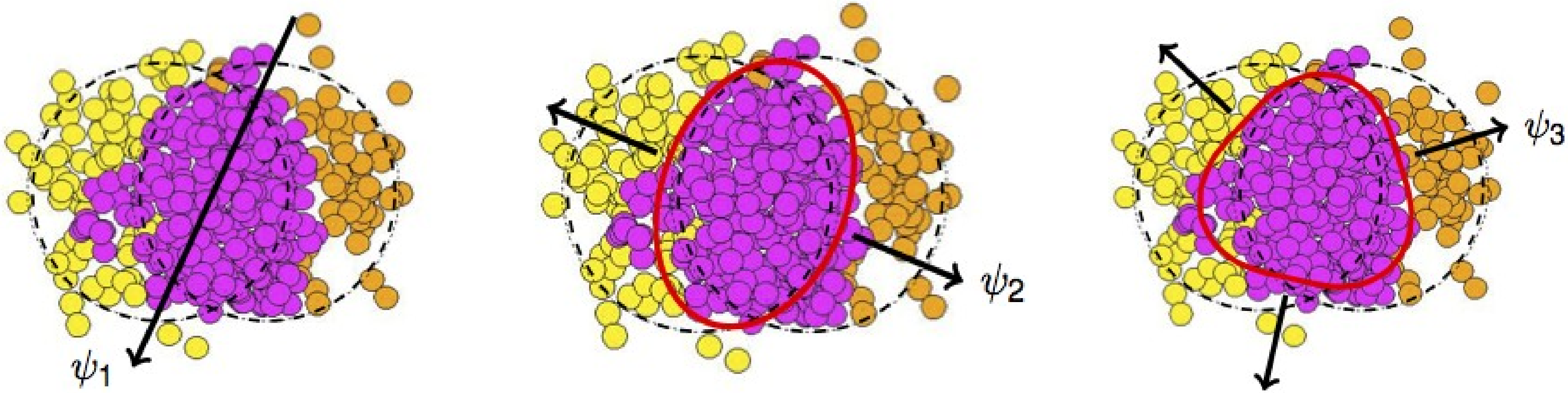
B. Schenke et al., PRL 106 (2011) 042301



Initial conditions | Ideal hydrodynamics | Viscous hydrodynamics

- Most central collision: fluctuations of participating nucleons
  - Higher (odd) harmonics since $\Psi_{RP} \rightarrow \Psi_n$ (n-th order symmetry plane)
- Anisotropic flow: the transfer of initial spatial anisotropy into the final anisotropy in momentum space via collective interactions
  - Sensitive to the system evolution
    - Constrain initial conditions, equation-of-state (EOS), transport properties

Quantifying anisotropic flow



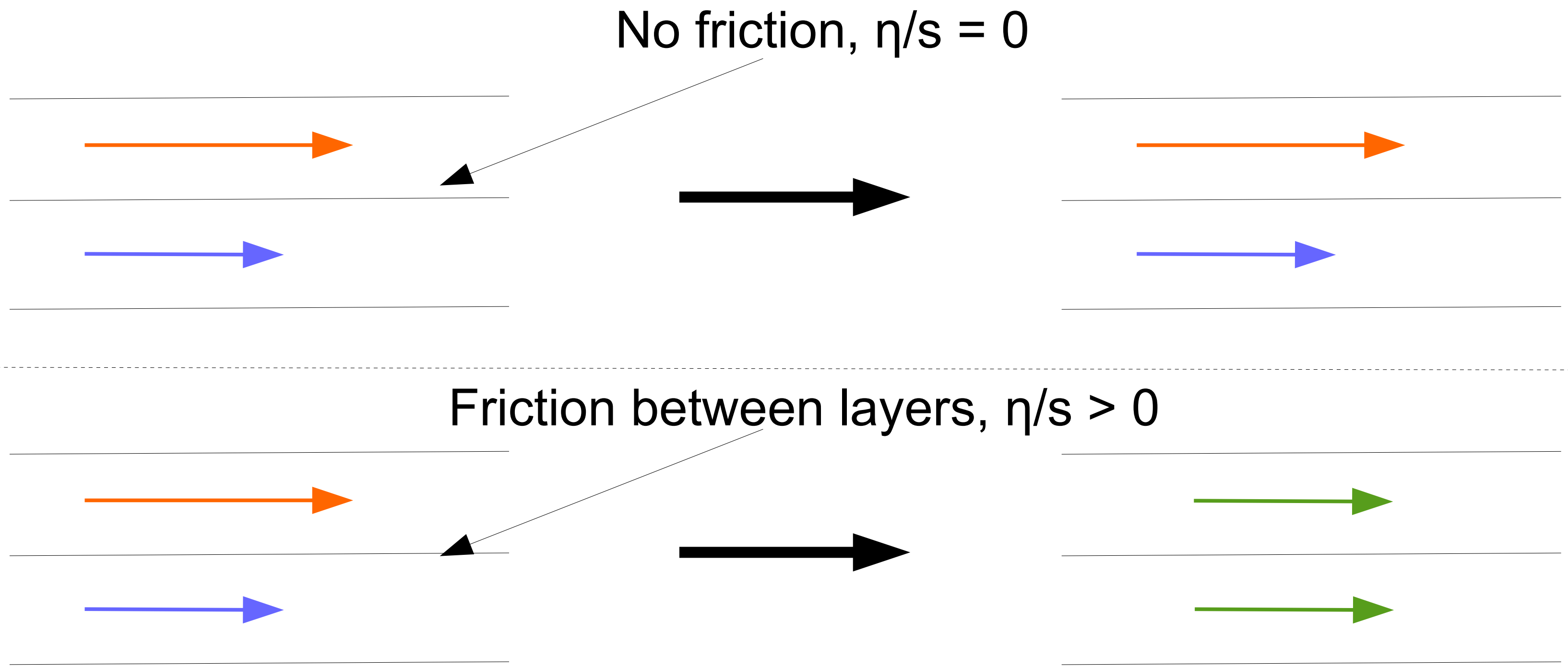
M. Luzum, J. Phys. G: Nucl. Part. Phys. 38 (2011) 124026

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

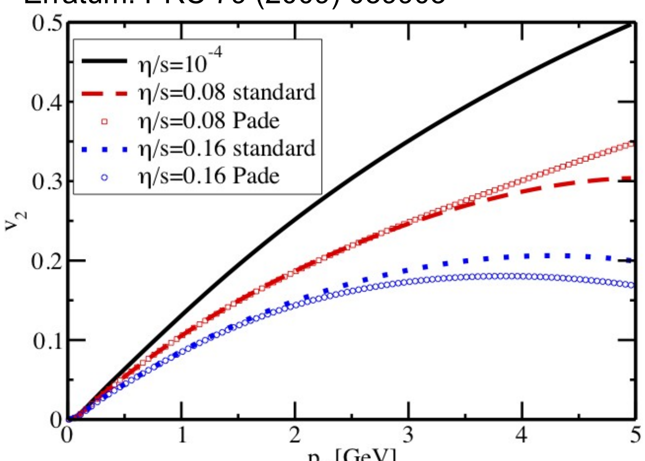
$$v_n = \langle \cos\left(n\left(\varphi - \Psi_n\right)\right)\rangle$$

- Particle azimuthal distribution measured with respect to the symmetry plane is not isotropic → Fourier series   S. Voloshin and Y. Zhang, Z. Phys. C 70, (1996) 665
- v_n quantify the event anisotropy
  - v_1 directed flow, v_2 elliptic flow, v_3 triangular flow, ...

Shear viscosity over entropy density (η/s)



M. Luzum and P. Romatschke, PRC 78 (2008) 034915
Erratum: PRC 79 (2009) 039903



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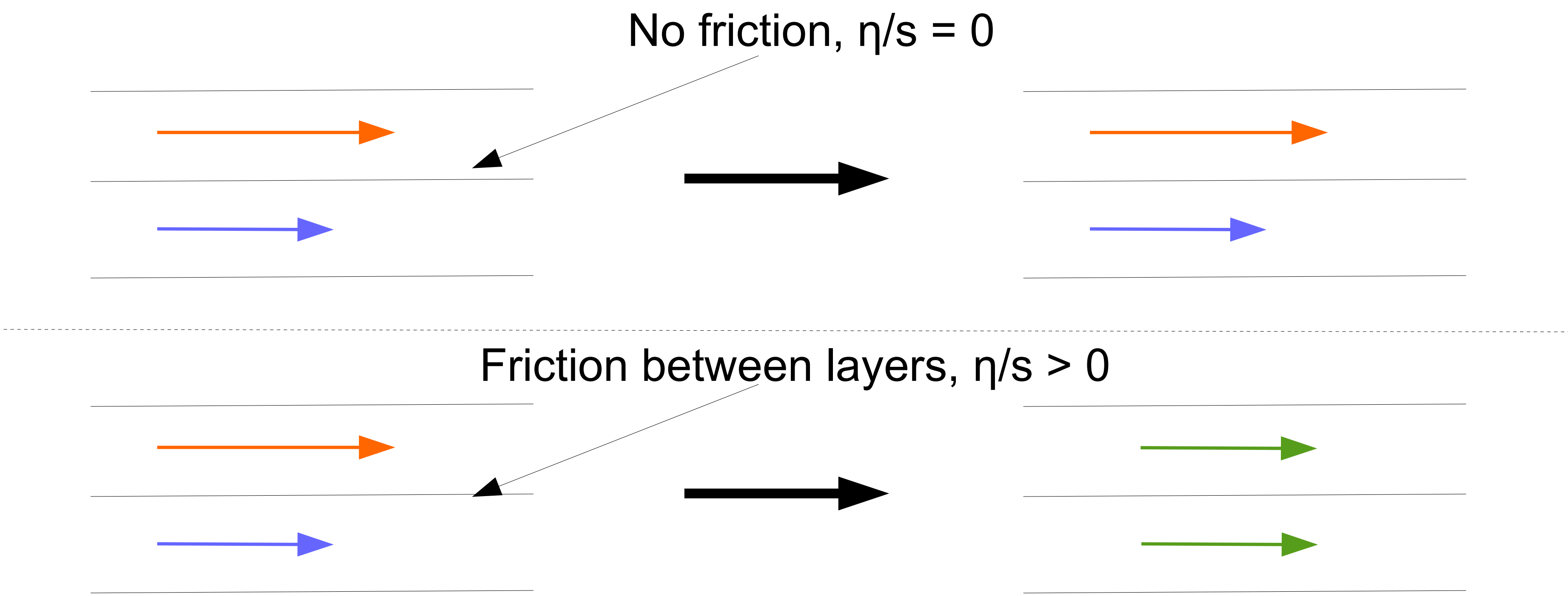
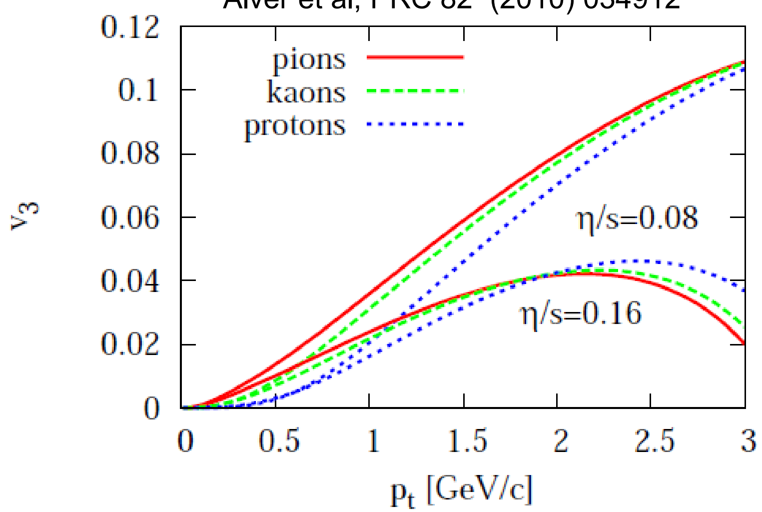


Alver et al, PRC 82 (2010) 034912



- Shear viscosity will make the velocities u_1, u_2, u_3 equal and destroy the elliptic flow
- Higher harmonics get destroyed more easily due to small differences between velocities → sensitive probes to η/s

Flow fluctuations

- 2- and 4-particle azimuthal correlations for an event

$$\langle 2\rangle \equiv \langle \cos(n(\varphi_i - \varphi_j))\rangle, i \neq j$$
$$\langle 4\rangle \equiv \langle \cos(n(\varphi_i + \varphi_j - \varphi_k - \varphi_l))\rangle, i \neq j \neq k \neq l$$

- Averaging over all events, the 2nd and 4th order cumulants

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

- Flow fluctuations: affect methods differently

$$v_n\{2\} \approx \langle v_n\rangle + \sigma_{v_n}^2/(2v_n)$$
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  - For Bessel-Gaussian fluctuations

S. Voloshin et al., PLB 659 (2008) 537

$$v_n\{2\}^2 = v_{n,0}^2 + 2\sigma_{vn}^2$$
$$v_n\{m\} = v_{n,0}, m \geqslant 4$$

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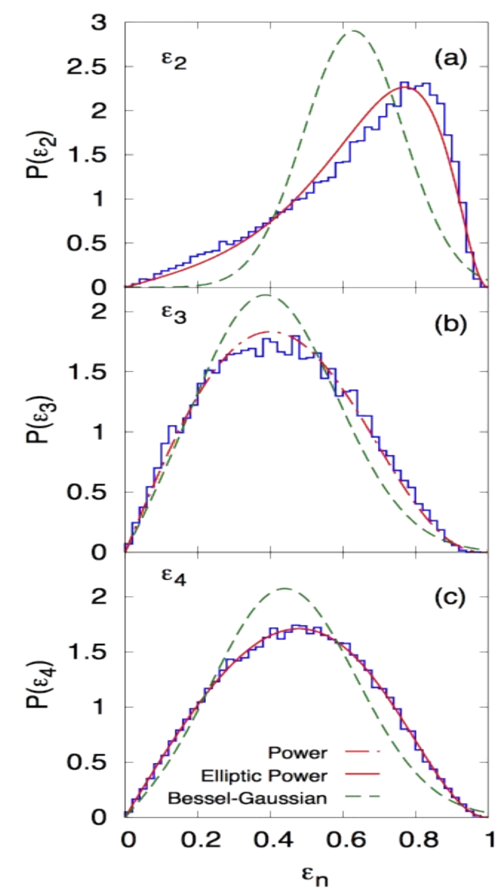
S. Voloshin et al., PLB 659 (2008) 537

  - Other parametrizations available

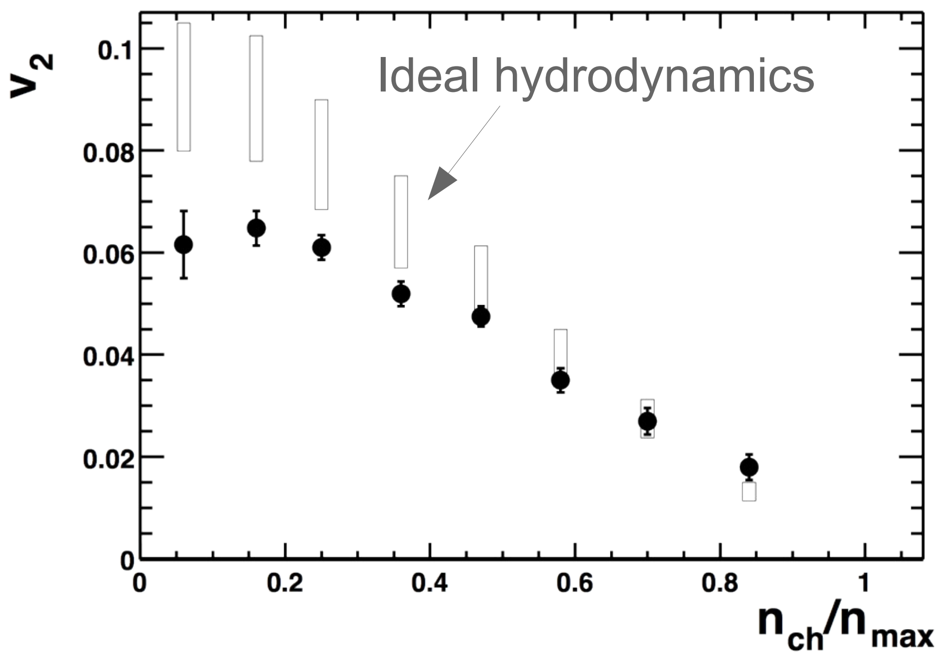
L. Yan and J.Y. Ollitrault, PRL 112 (2014) 082301
L. Yan et al., PRC 90 (2014) 024903



v_n measurements

First v_2 @ RHIC

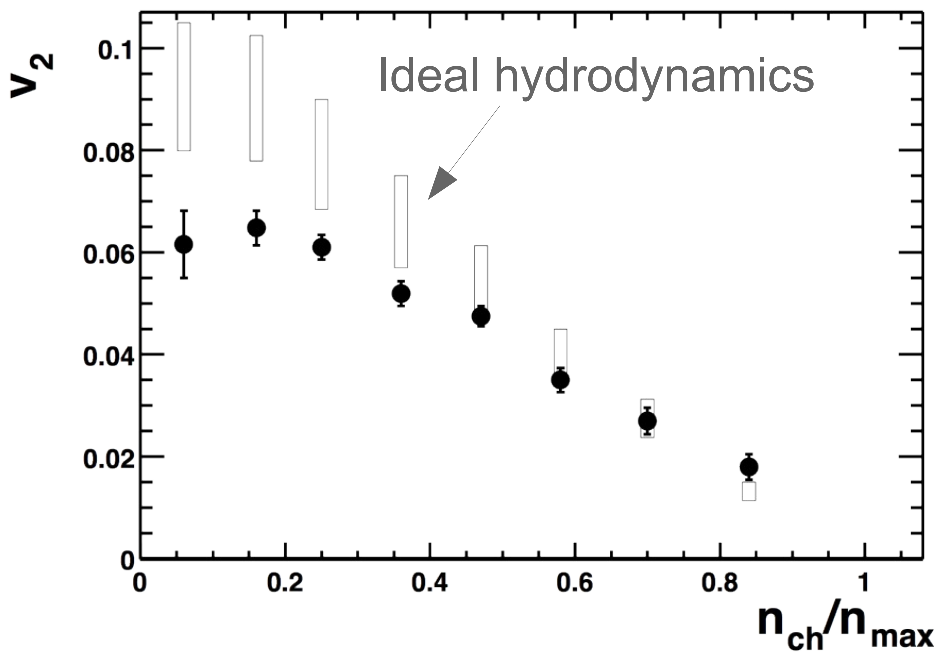
STAR, PRL 86 (2001) 402

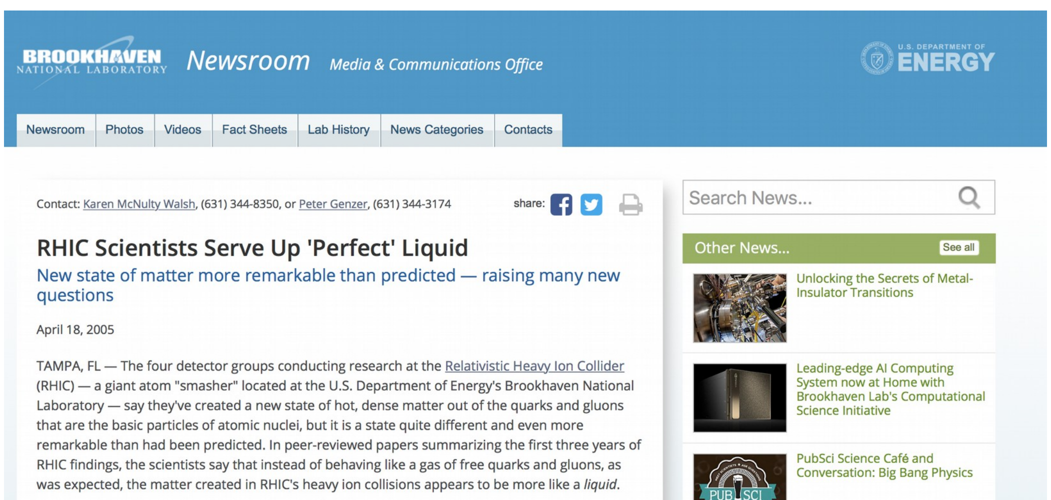


- First v_2 measurement @ RHIC
  - Good agreement with hydrodynamic predictions with η/s=0

First v_2 @ RHIC

STAR, PRL 86 (2001) 402





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RHIC Scientists Serve Up 'Perfect' Liquid

New state of matter more remarkable than predicted — raising many new questions

April 18, 2005

TAMPA, FL — The four detector groups conducting research at the Relativistic Heavy Ion Collider (RHIC) — a giant atom "smasher" located at the U.S. Department of Energy's Brookhaven National Laboratory — say they've created a new state of hot, dense matter out of the quarks and gluons that are the basic particles of atomic nuclei, but it is a state quite different and even more remarkable than had been predicted. In peer-reviewed papers summarizing the first three years of RHIC findings, the scientists say that instead of behaving like a gas of free quarks and gluons, as was expected, the matter created in RHIC's heavy ion collisions appears to be more like a *liquid*.

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Leading-edge AI Computing System now at Home with Brookhaven Lab's Computational Science Initiative

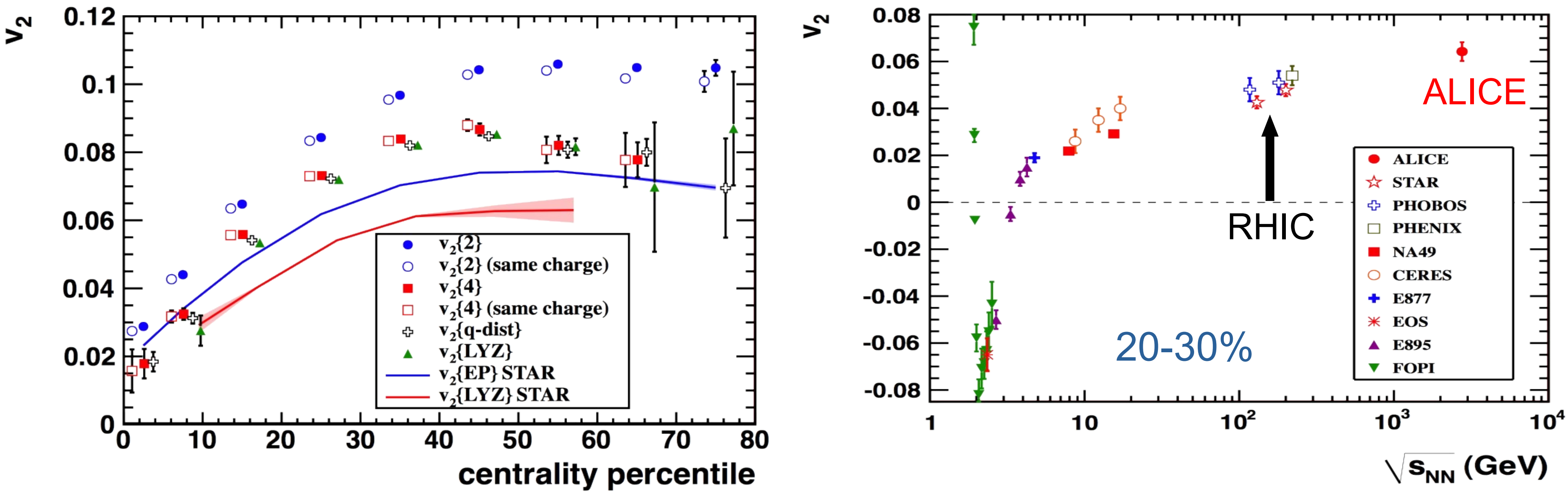
PubSci Science Café and Conversation: Big Bang Physics

- First v_2 measurement @ RHIC
  - Good agreement with hydrodynamic predictions with $\eta/s=0$

    → "Perfect" liquid (almost zero friction)

First v_2 @ LHC

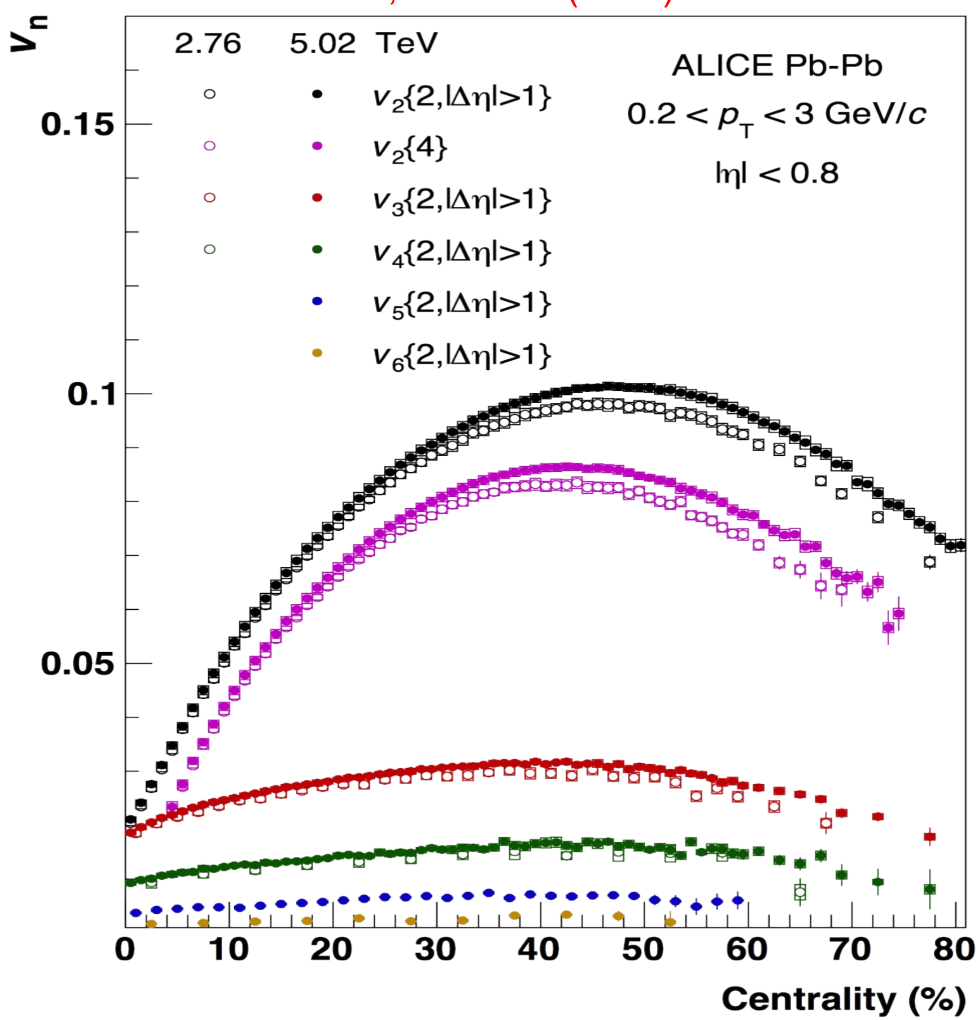
ALICE, PRL 105 (2010) 252302



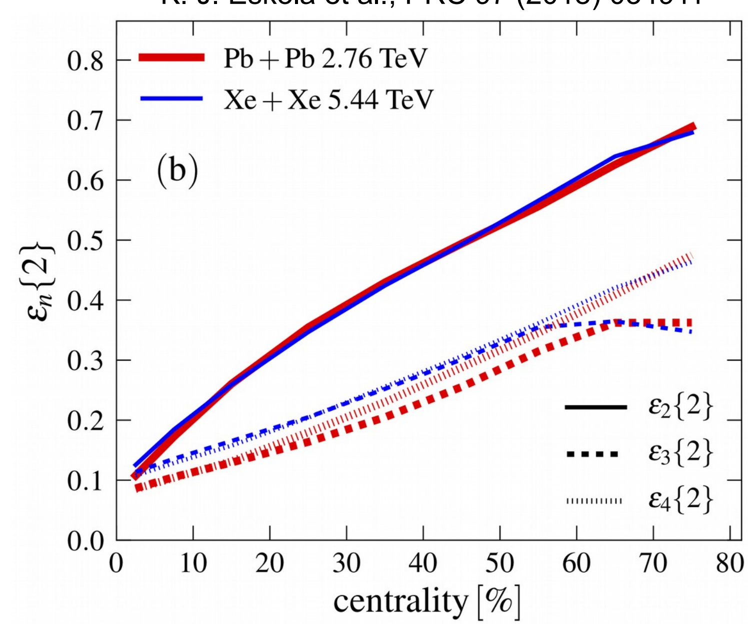
- First v_2 measurement @ LHC
  - Elliptic flow increases by ~30% when compared to RHIC energies
    - The system created at the LHC behaves like a “perfect” liquid

Integrated v_n

ALICE, JHEP 07 (2018) 103



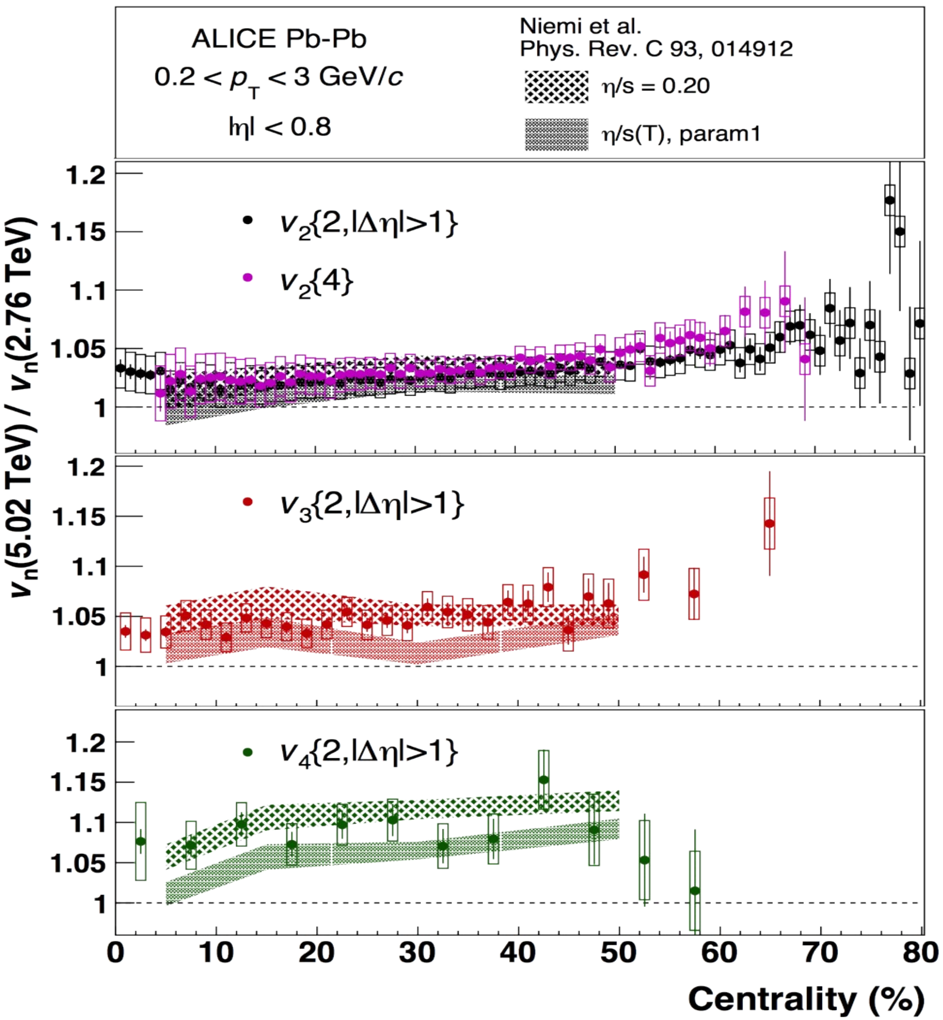
K. J. Eskola et al., PRC 97 (2018) 034911



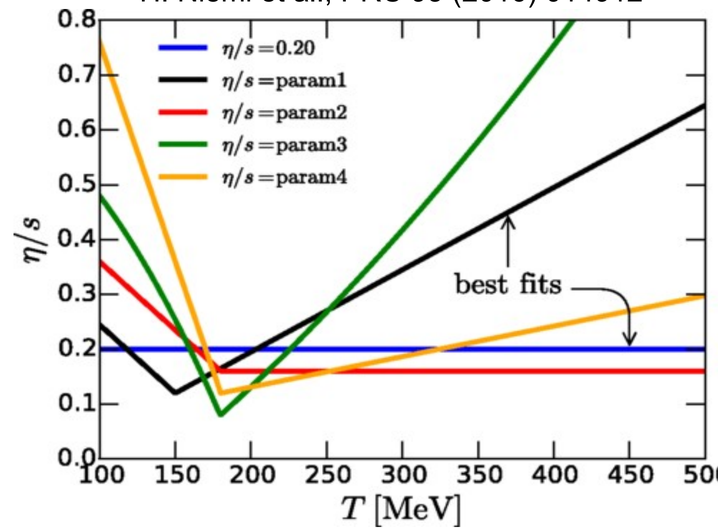
- Integrated v_n measured up to v_6 using cumulants
  - Increase of $\langle p_T \rangle$ responsible for differences between $\sqrt{s_{NN}}$ = 2.76 TeV and 5.02 TeV

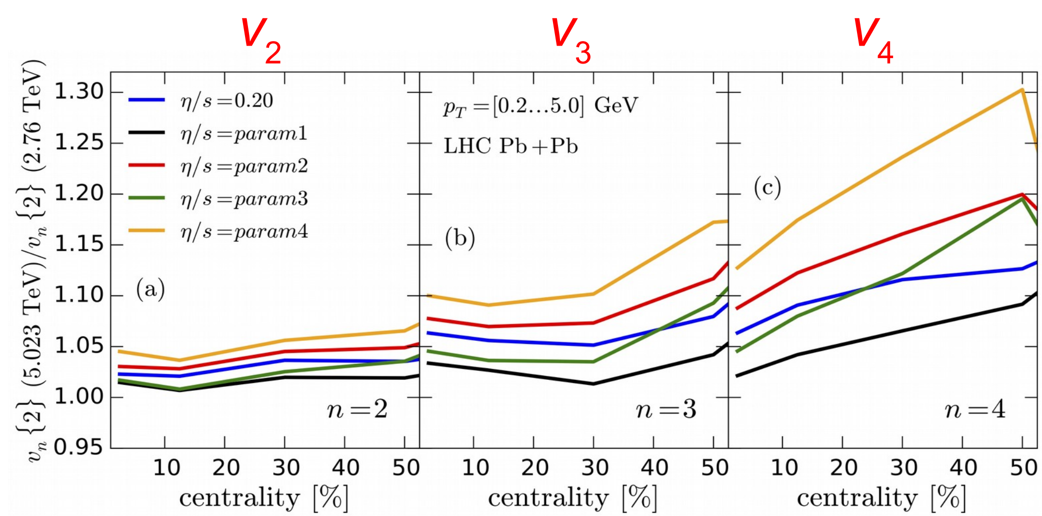
Integrated v_n

ALICE, JHEP 07 (2018) 103



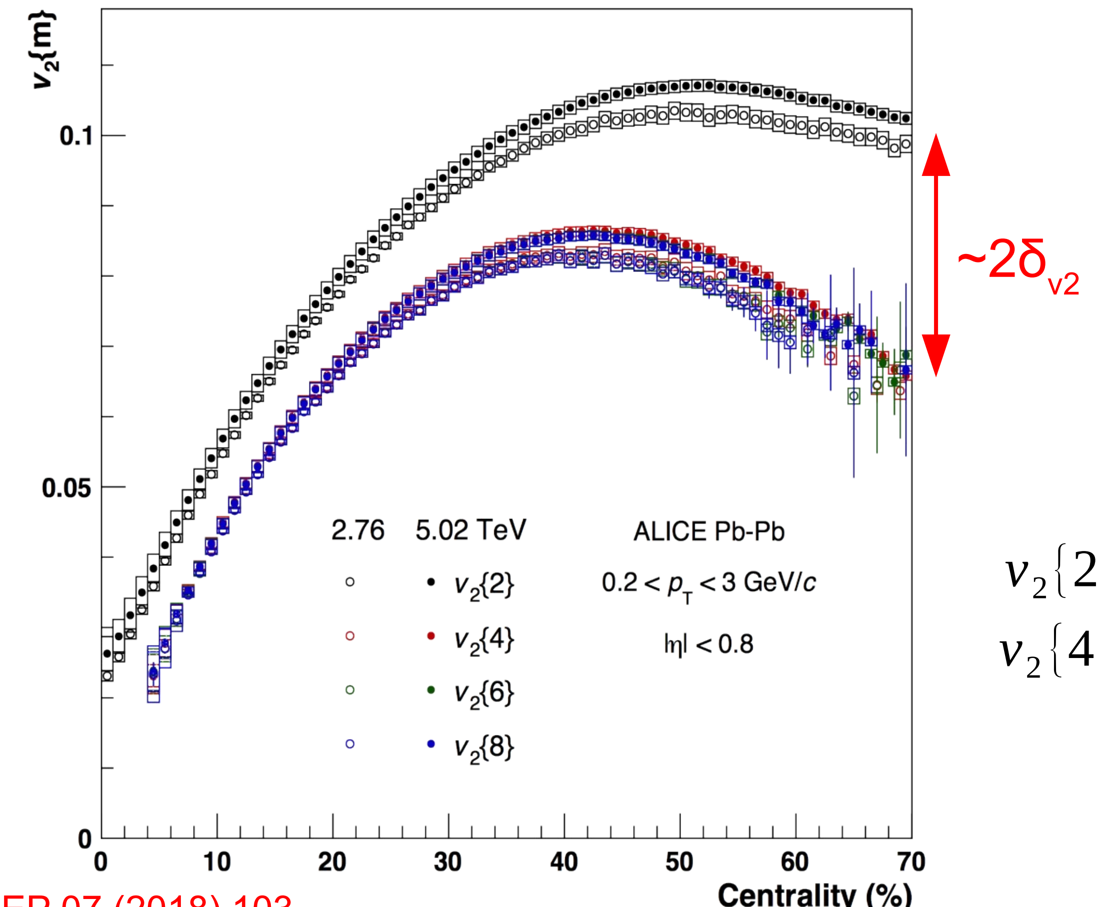
H. Niemi et al., PRC 93 (2016) 014912





- Integrated v_n measured up to v_6 using cumulants
  - Increase of $\langle p_T \rangle$ responsible for differences between $\sqrt{s_{NN}}$ = 2.76 TeV and 5.02 TeV
  - Ratios of v_n at different energies constrain initial conditions and η/s(T)

Integrated v_2: cumulants



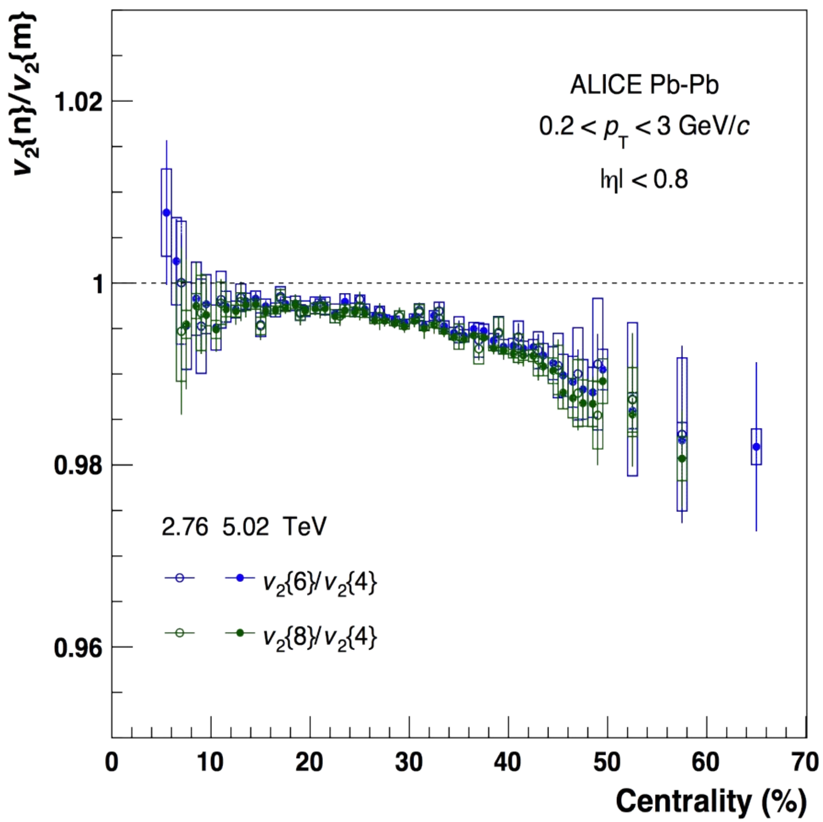
ALICE, JHEP 07 (2018) 103

$$v_2\{2\} \approx \langle v_2 \rangle + \sigma_{v_2}^2 / (2 v_2)$$
$$v_2\{4\} \approx \langle v_2 \rangle - \sigma_{v_2}^2 / (2 v_2)$$

- Integrated v_2 measured with 2-, 4-, 6-, 8-particle cumulants
  - Different sensitivities to flow fluctuations
  - Allow to extract flow probability distribution function (p.d.f.)
  - Increase of $\langle p_T \rangle$ responsible for differences between $\sqrt{s_{NN}}$ = 2.76 TeV and 5.02 TeV

Integrated v_2: ratios of cumulants

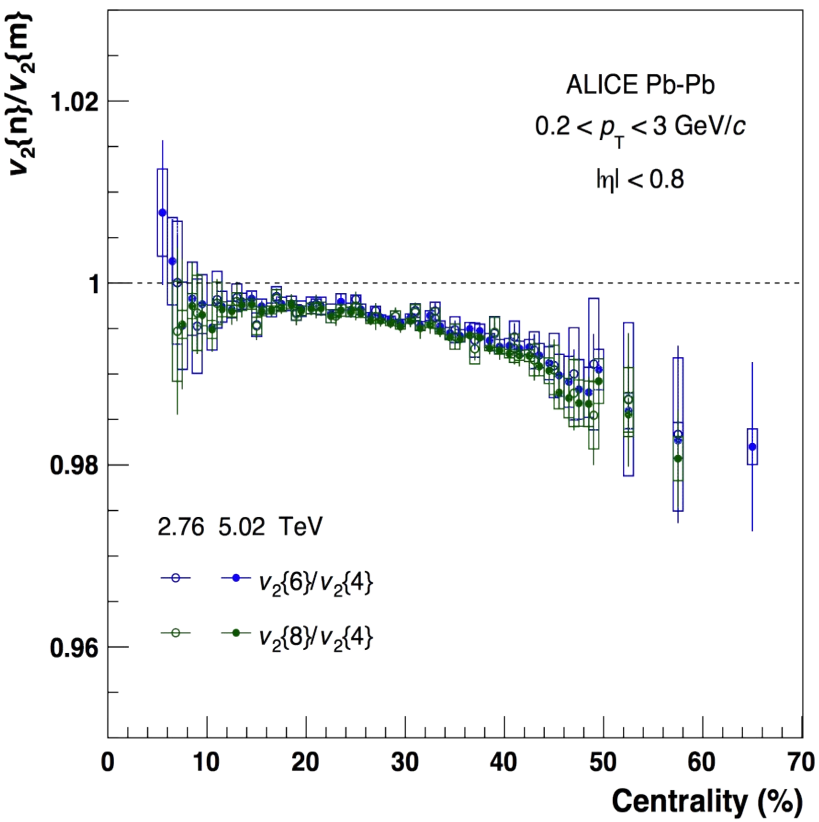
ALICE, JHEP 07 (2018) 103

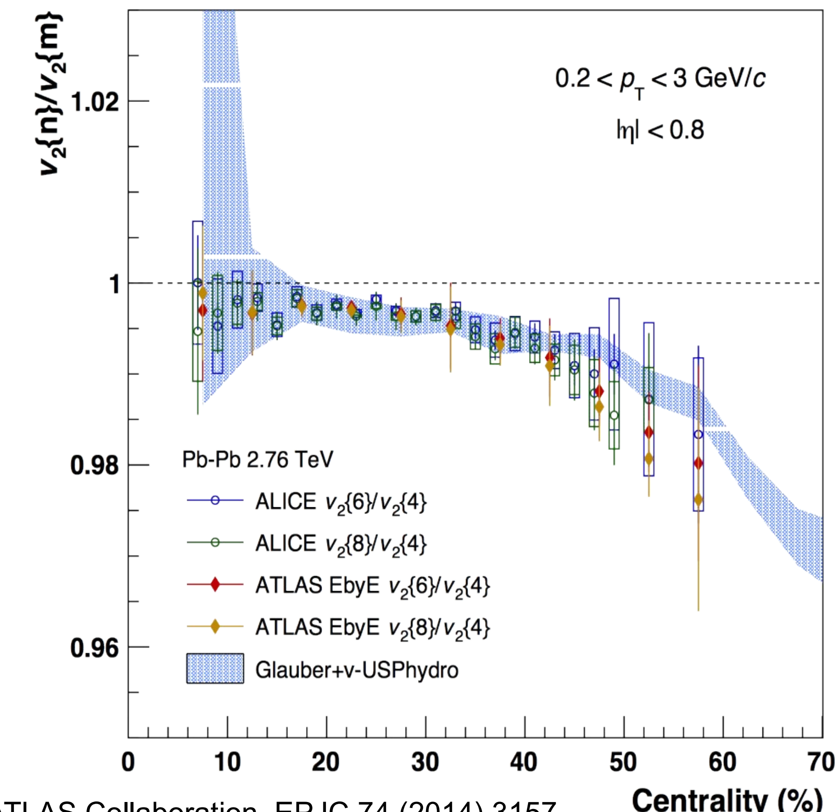


- Ratios $v_2\{6\}/v_2\{4\}$ and $v_2\{8\}/v_2\{4\}$ below unity → non-Gaussian fluctuations
  - Small centrality dependence consistent between $\sqrt{s_{NN}}$ = 2.76 TeV and 5.02 TeV

Integrated v_2: ratios of cumulants

ALICE, JHEP 07 (2018) 103



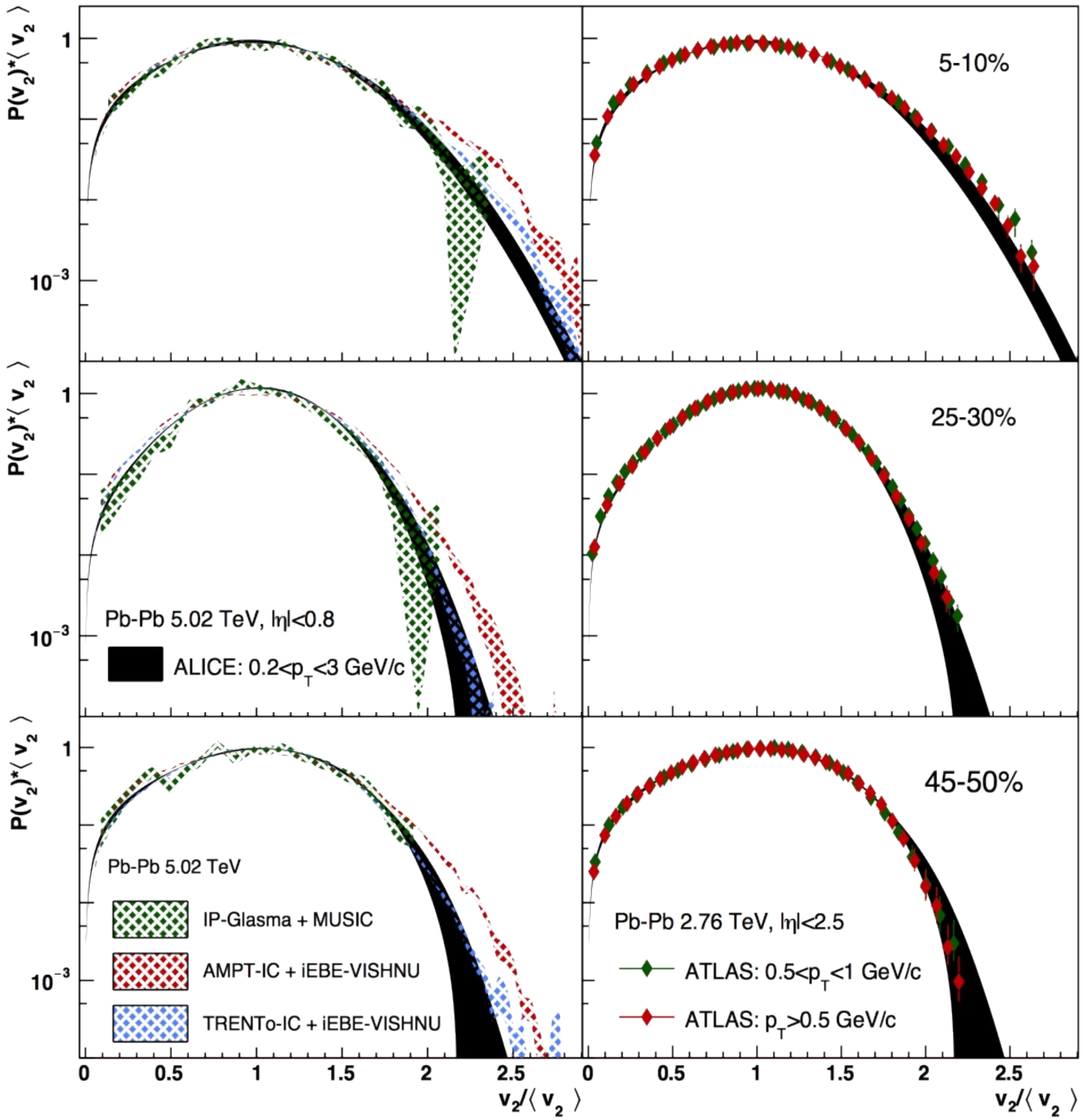


ATLAS Collaboration, EPJC 74 (2014) 3157
G. Giacalone et al., PRC 95 (2017) 014913

- Ratios $v_2\{6\}/v_2\{4\}$ and $v_2\{8\}/v_2\{4\}$ below unity → non-Gaussian fluctuations
  - Small centrality dependence consistent between $\sqrt{s_{NN}}$ = 2.76 TeV and 5.02 TeV
  - Good agreement with ATLAS results and hydrodynamic calculations

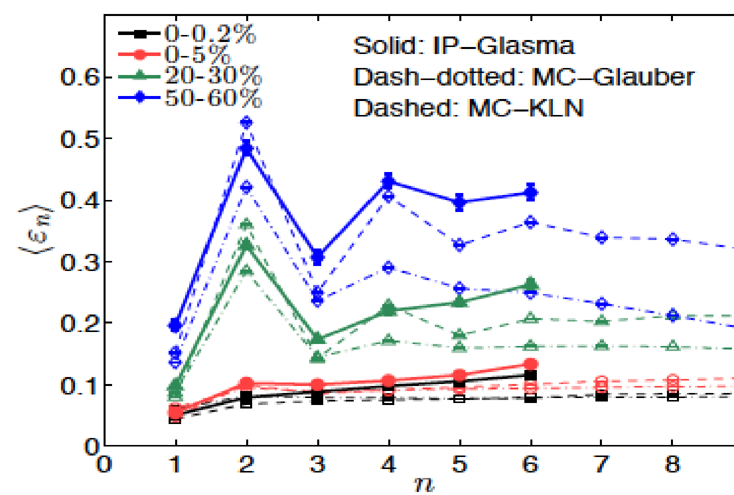
v_2 p.d.f.

ALICE, JHEP 07 (2018) 103



ATLAS, JHEP 11 (2013) 183
S. McDonald et al., PRC 95 (2017) 064913
W. Zhao et al., EPJC 77 (2017) 645

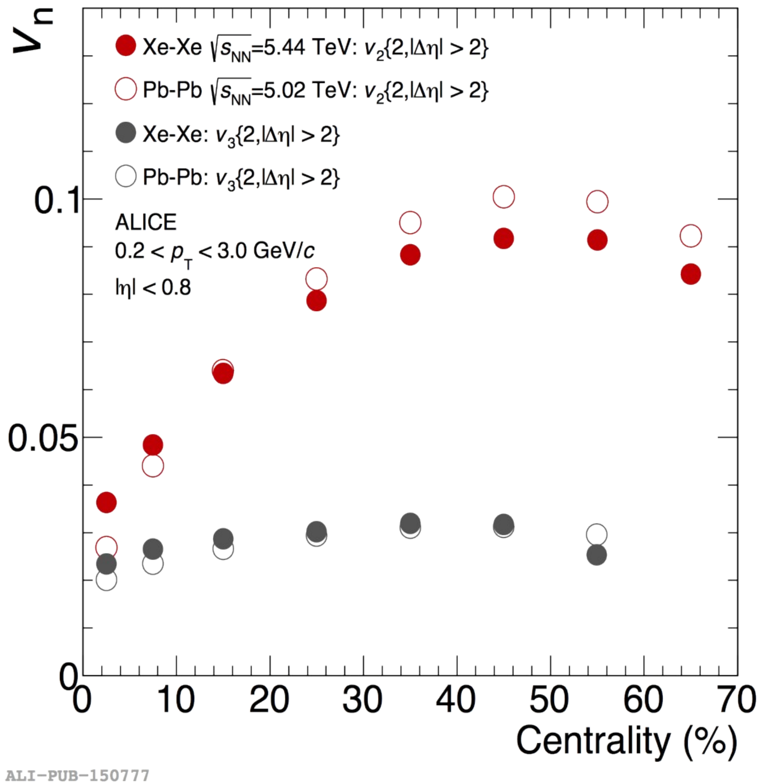
- Use $v_2\{m\}$ to determine v_2 p.d.f $P(v_2)$
- $P(v_2)$ scaled by $<v_2>$ agrees with ATLAS results at $\sqrt{s_{NN}}$ = 2.76 TeV
  - Flow fluctuations at low p_T depend weakly on p_T and collision energy
- Good agreement with hydrodynamic calculations with TRENTo and IP-Glasma initial conditions
  - Constrain initial state models



U. Heinz and R. Snellings, Ann.Rev.Nucl.Part.Sci. 63 (2013) 123

v_n: Pb-Pb vs Xe-Xe

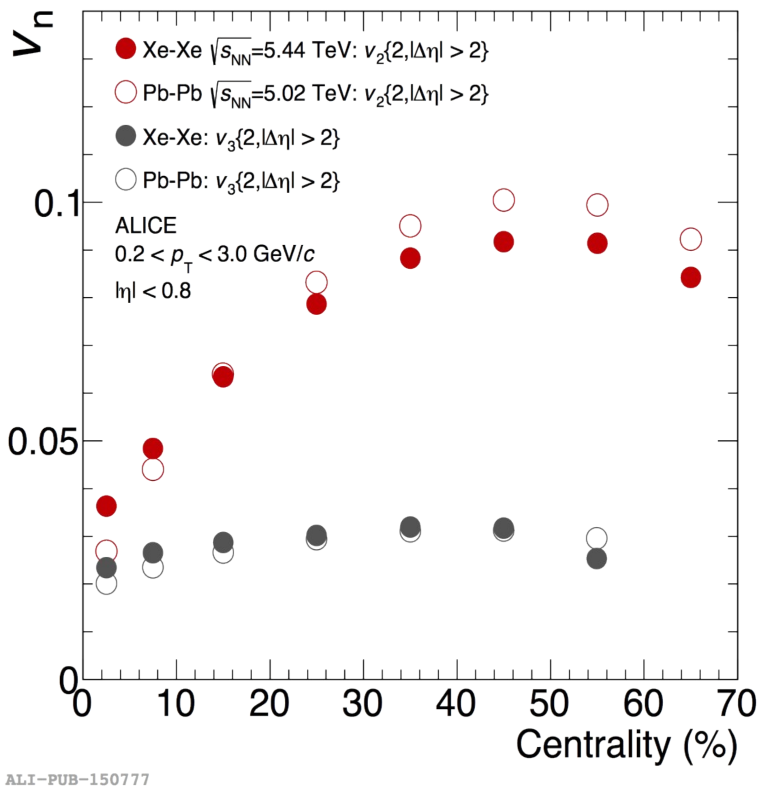
ALICE, PLB 784 (2018) 82



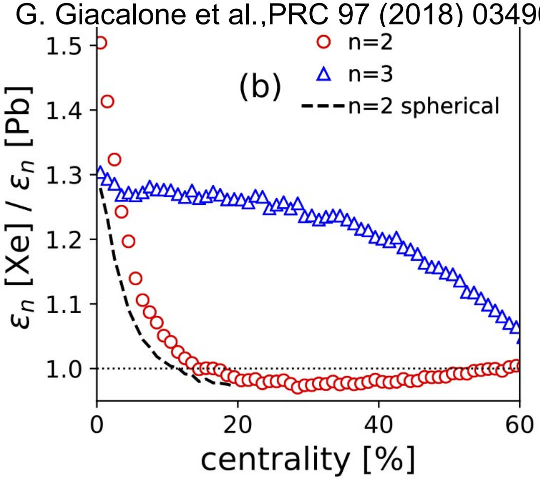
- v_2: differences within 10% except in 0-5% centrality interval where reached 35% (Xe deformation)

v_n: Pb-Pb vs Xe-Xe

ALICE, PLB 784 (2018) 82



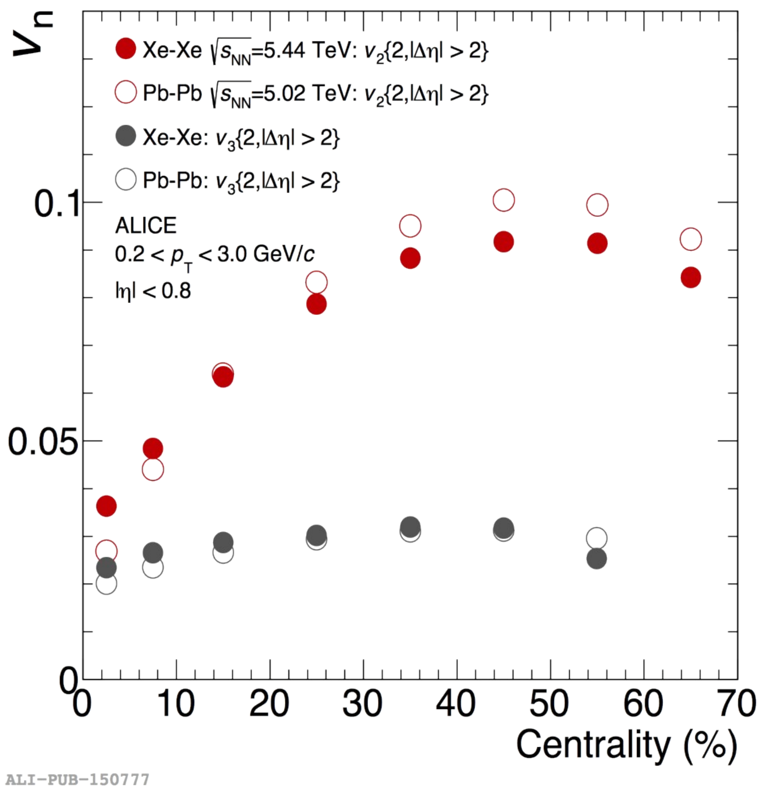
G. Giacalone et al.,PRC 97 (2018) 034904

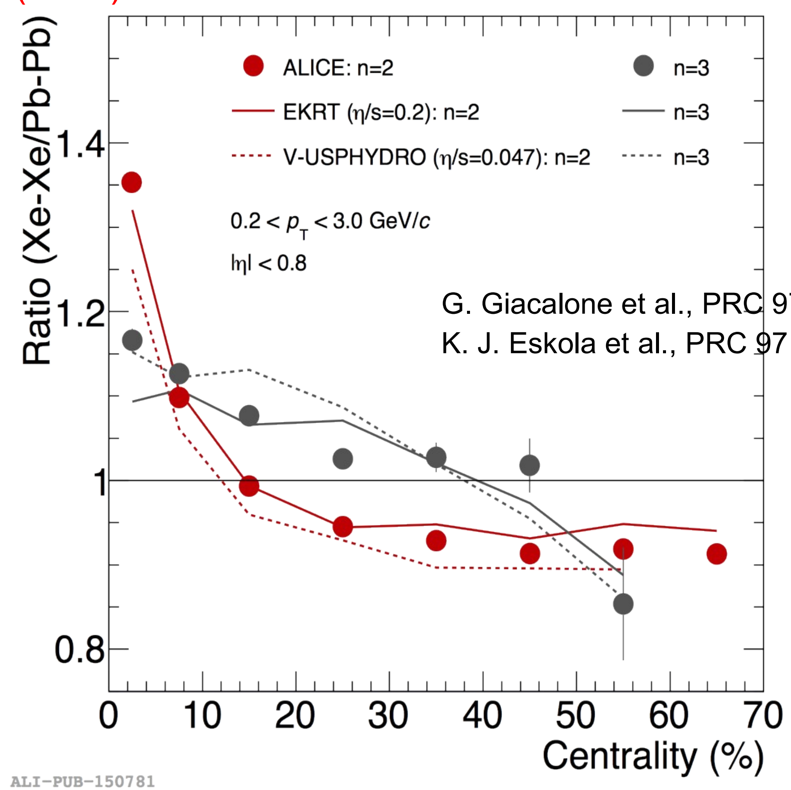


- v_2: differences within 10% except in 0-5% centrality interval where reached 35% (Xe deformation)
- v_3: larger in Xe-Xe due to larger initial state fluctuations

v_n: Pb-Pb vs Xe-Xe

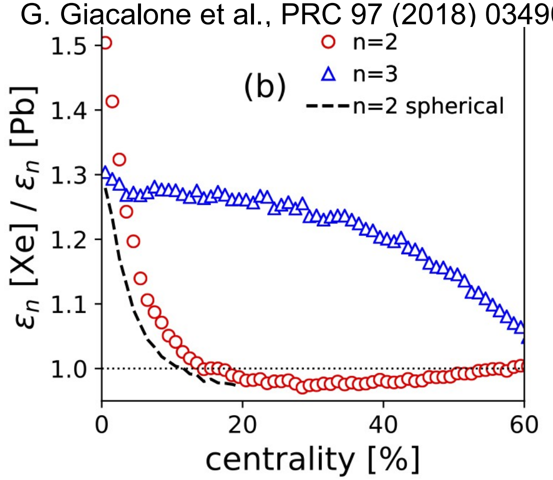
ALICE, PLB 784 (2018) 82





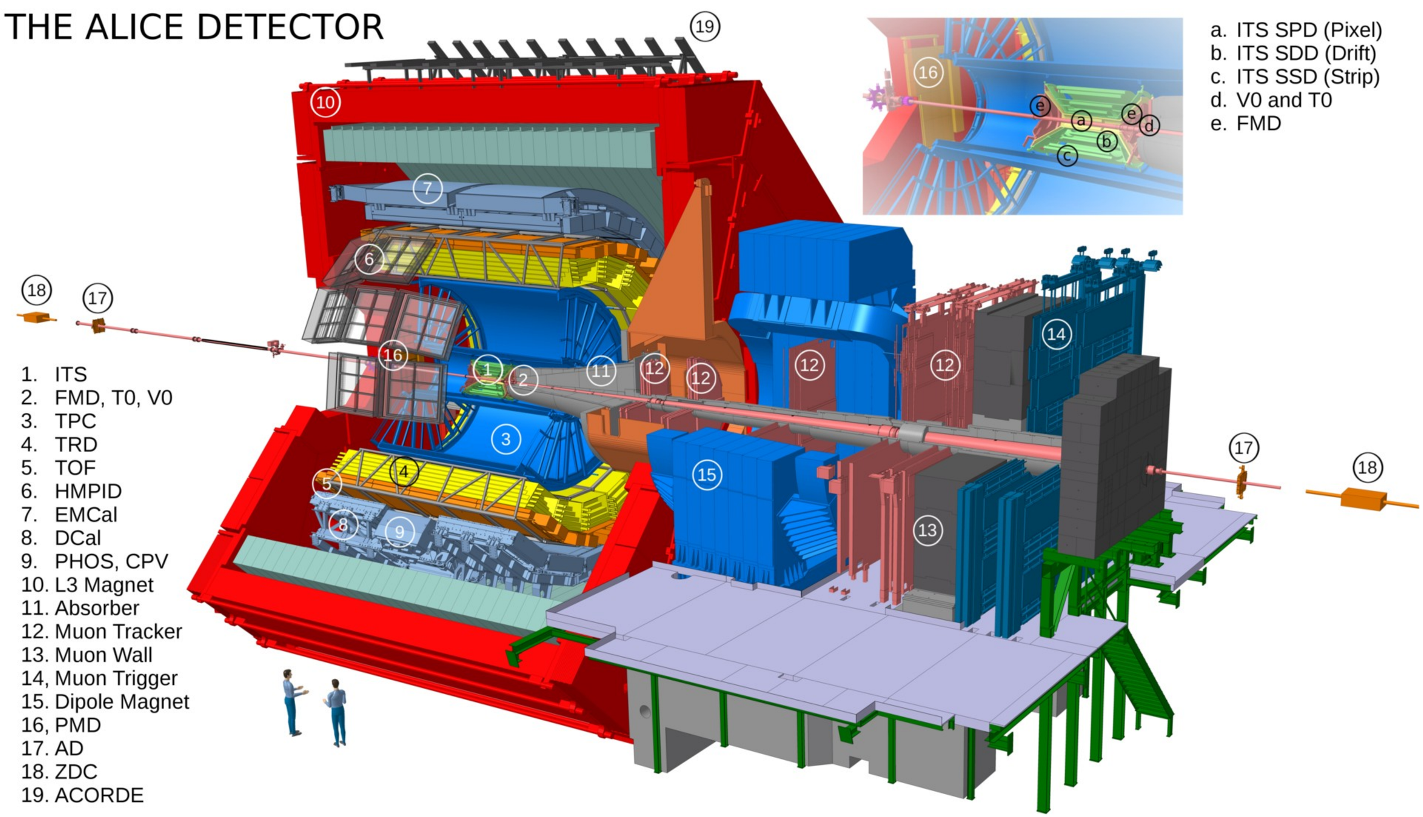
G. Giacalone et al., PRC 97 (2018) 034904
K. J. Eskola et al., PRC 97 (2018) 034911

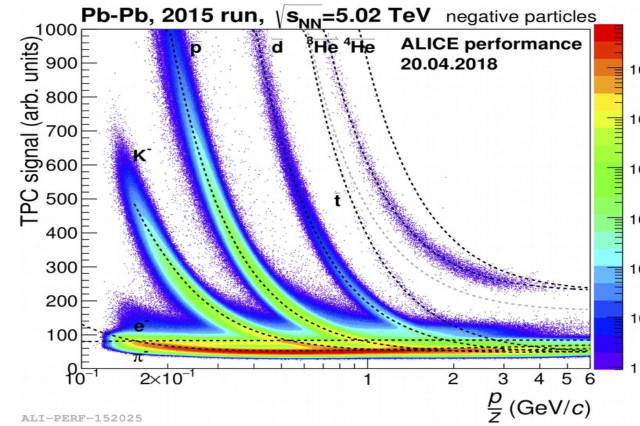
G. Giacalone et al., PRC 97 (2018) 034904

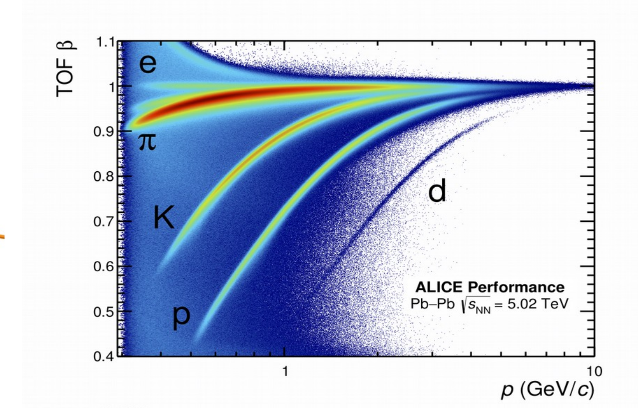


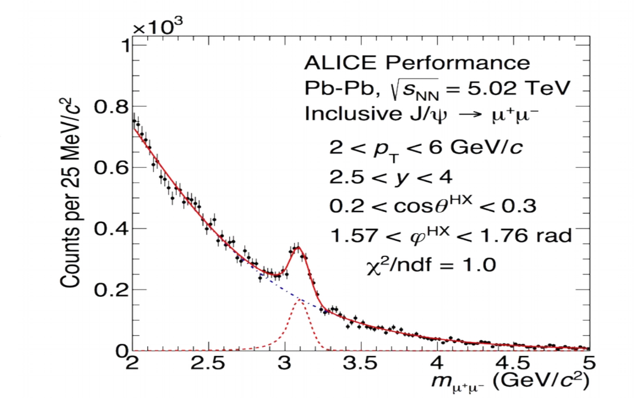
- v_2: differences within 10% except in 0-5% centrality interval where reached 35% (Xe deformation)
- v_3: larger in Xe-Xe due to larger initial state fluctuations
- Results described quantitatively by hydrodynamic models

Particle identification (PID) in ALICE



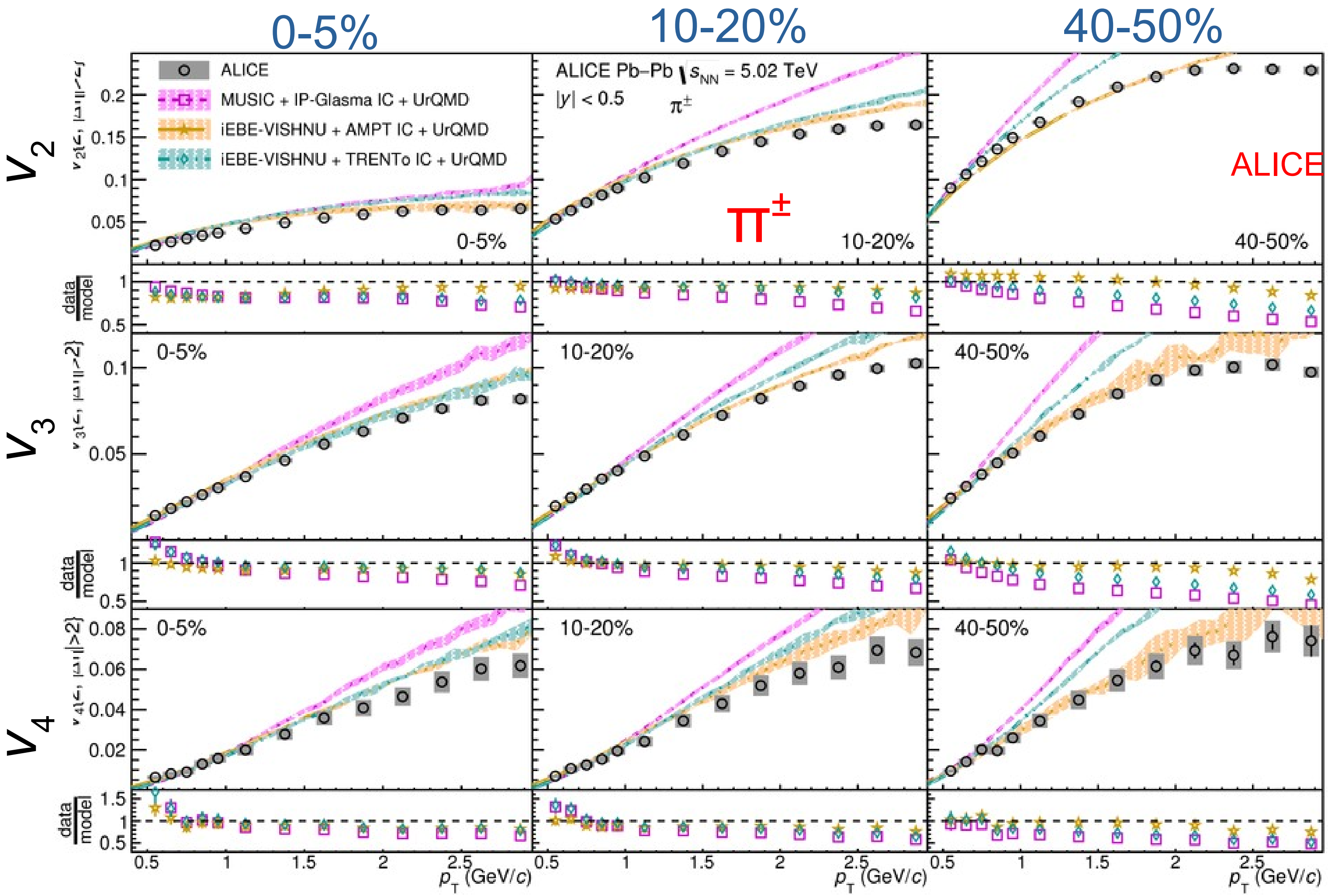






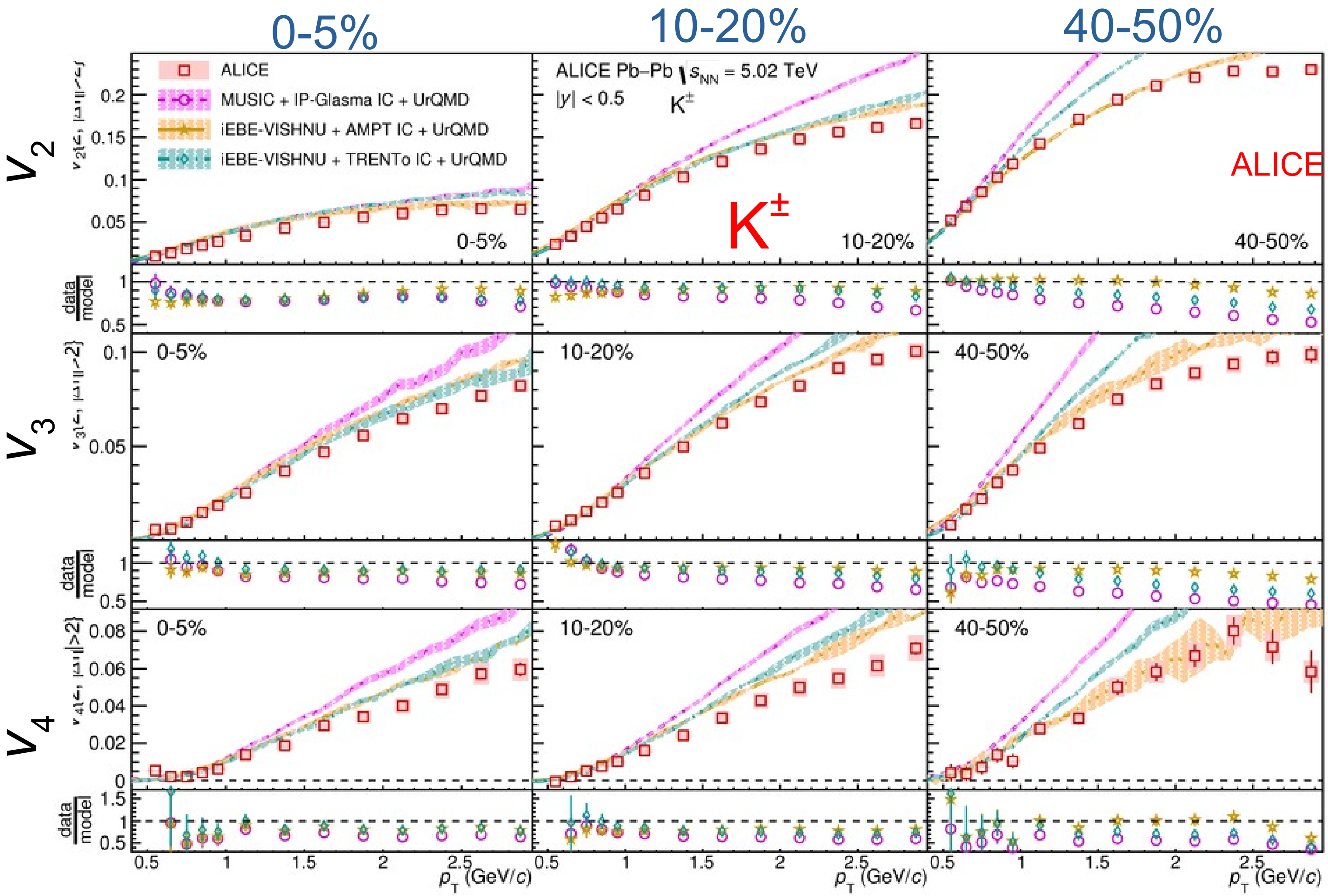
- $\pi^{\pm}$, $K^{\pm}$, p identified using TPC and TOF
- Topological reconstruction for K^0_S, Λ, J/Ψ and D-mesons

$\pi^{\pm}$ v_n vs hydrodynamic calculations



- Hydrodynamic calculations coupled to a hadronic cascade model (UrQMD) describe data at low p_T
  - MUSIC with IP-Glasma IC, ζ/s(T), η/s=0.095 for p_T<1 GeV/c — S. McDonald et al., PRC 95 (2017) 064913
  - iEBE-VISHNU with AMPT IC, ζ/s=0, η/s=0.08 for p_T<2 GeV/c — W. Zhao et al., EPJC 77 (2017) 645
  - iEBE-VISHNU with TRENTo IC, ζ/s(T), η/s(T) for p_T<1-2 GeV/c

K$^{\pm}$ v_n vs hydrodynamic calculations



ALICE, JHEP 09 (2018) 006

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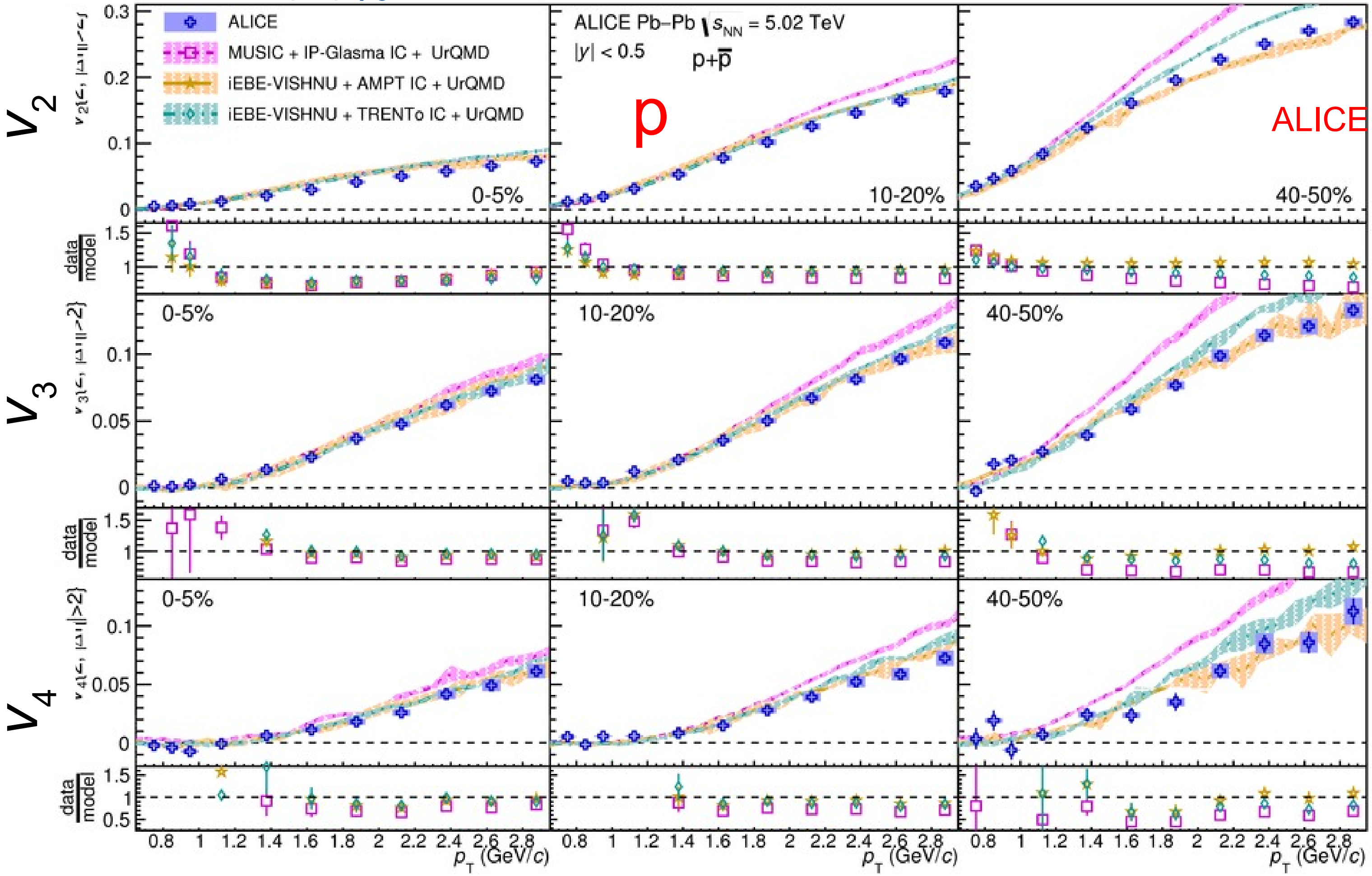
  - iEBE-VISHNU with AMPT IC, ζ/s=0, η/s=0.08 for p_T<2 GeV/*c* — W. Zhao et al., EPJC 77 (2017) 645
  - iEBE-VISHNU with TRENTo IC, ζ/s(T), η/s(T) for p_T<1-2 GeV/*c*

p v_n vs hydrodynamic calculations



ALICE, JHEP 09 (2018) 006

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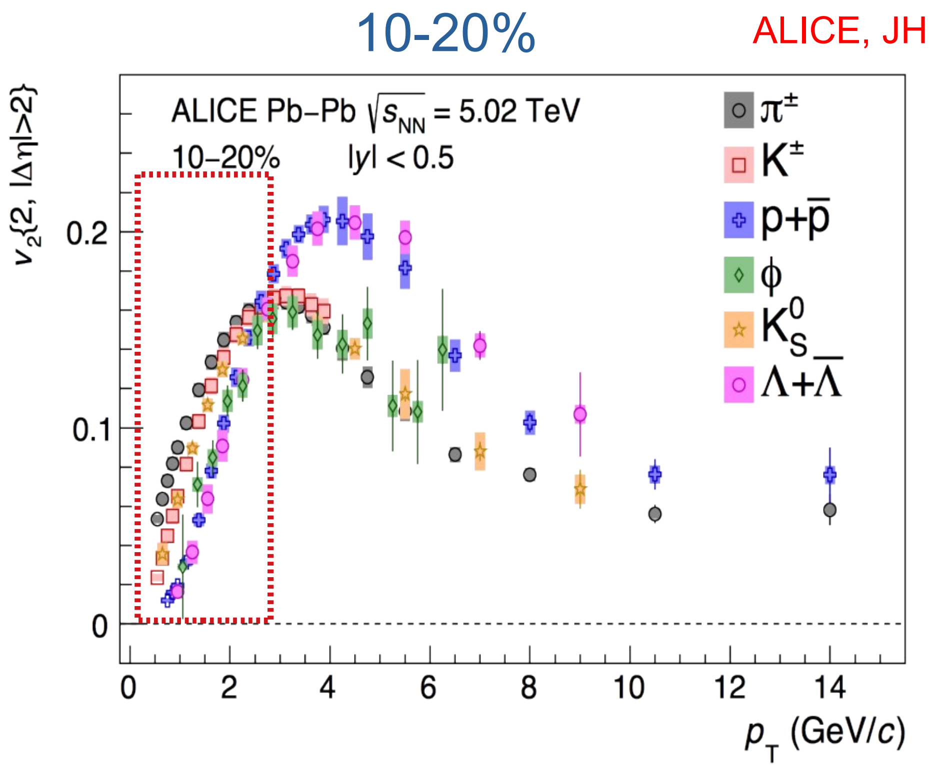
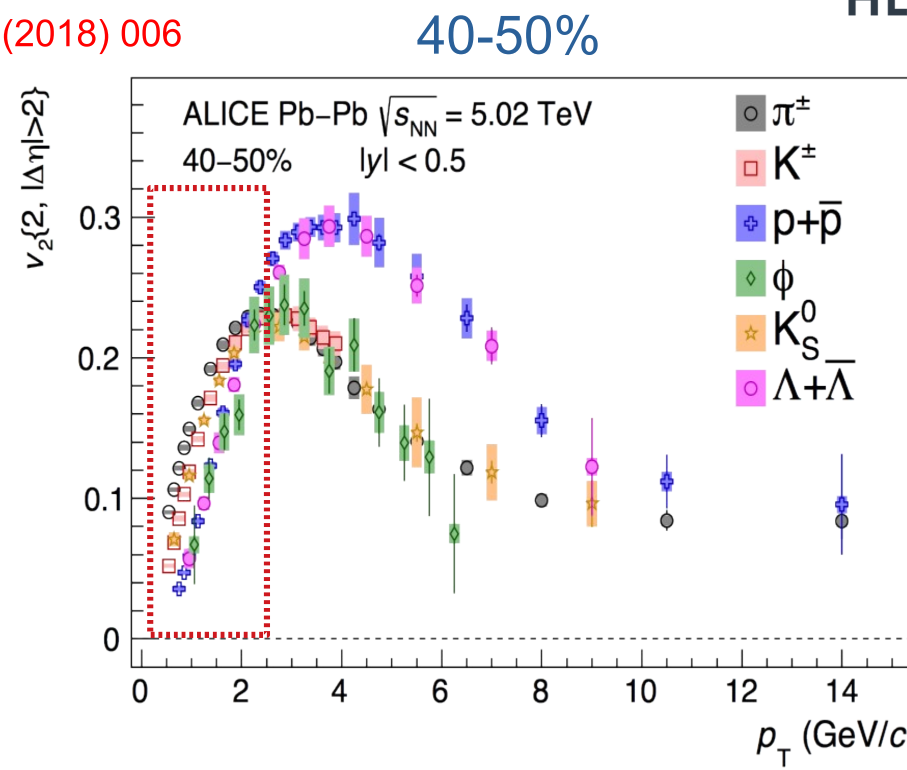
  - iEBE-VISHNU with AMPT IC, ζ/s=0, η/s=0.08 for p_T<3 GeV/c — W. Zhao et al., EPJC 77 (2017) 645
  - iEBE-VISHNU with TRENTo IC, ζ/s(T), η/s(T) for p_T<2-3 GeV/c

PID $v_2(p_T)$

ALICE, JHEP 09 (2018) 006





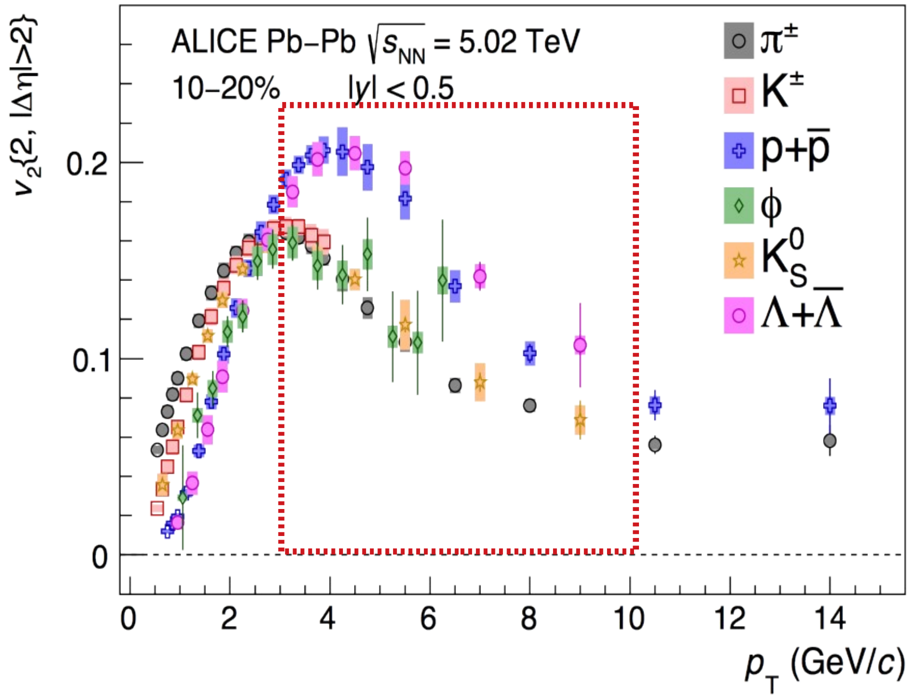
- For p_T<2 GeV/c: v_2 of lighter particles is larger than heavier ones → mass ordering
  - Interplay between elliptic and radial flow
    - Radial flow (isotropic expansion) pushes particles to higher p_T

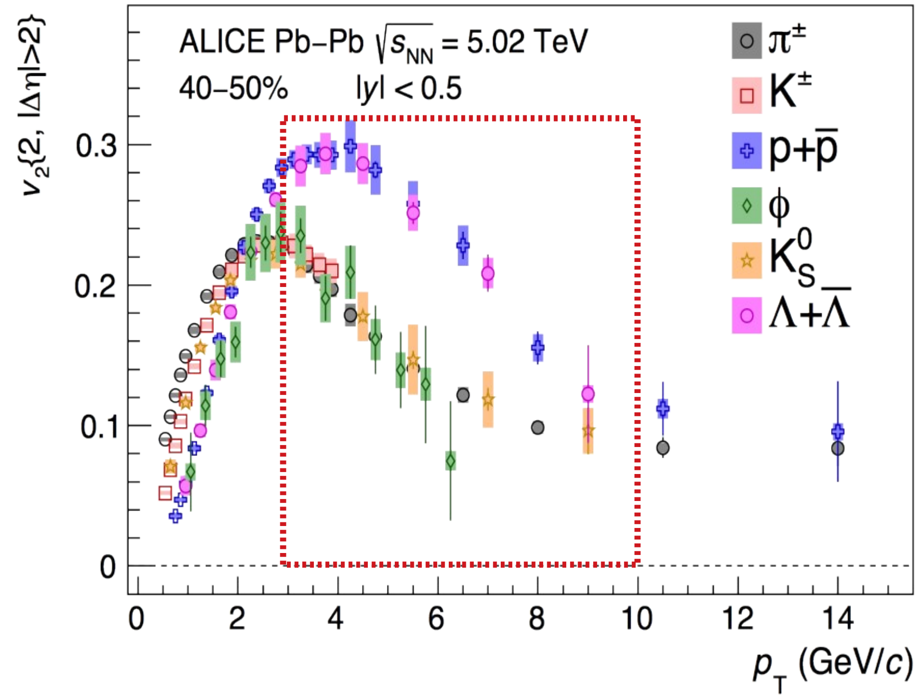
PID $v_2(p_T)$

10-20%

ALICE, JHEP 09 (2018) 006

40-50%

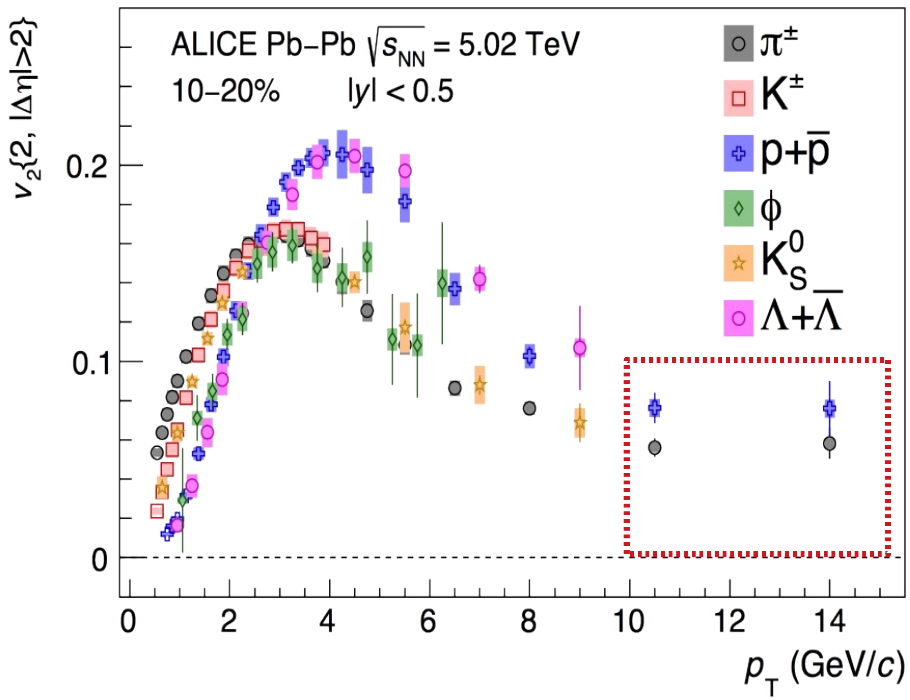


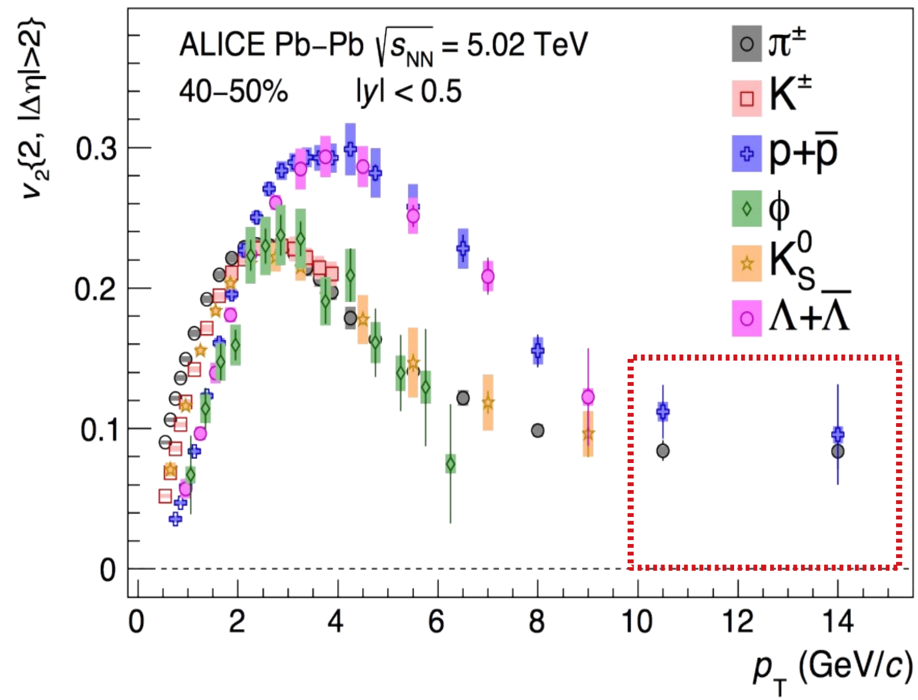


- For p_T<2 GeV/c: v_2 of lighter particles is larger than heavier ones → mass ordering
  - Interplay between elliptic and radial flow
    - Radial flow (isotropic expansion) pushes particles to higher p_T
- For 3<p_T<10 GeV/c: particles tend to group into mesons and baryons
- ϕ-meson (m ~ 1 GeV/c^2) v_2 tests both mass ordering and particle type scaling

PID $v_2(p_T)$

10-20% ALICE, JHEP 09 (2018) 006 40-50%





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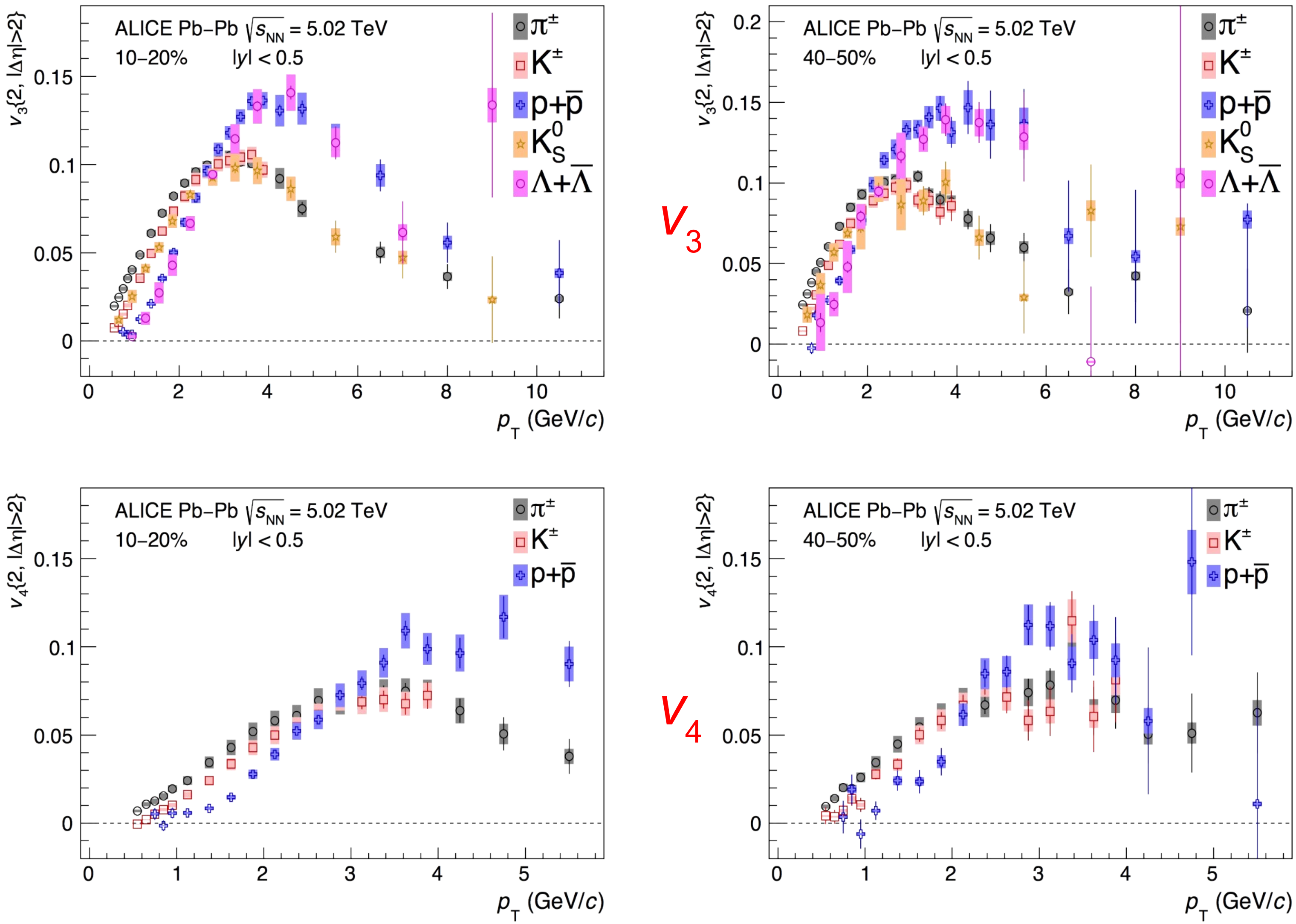
  - Interplay between elliptic and radial flow
    - Radial flow (isotropic expansion) pushes particles to higher p_T
- For 3<p_T<10 GeV/c: particles tend to group into mesons and baryons
- ϕ-meson (m ~ 1 GeV/c^2) v_2 tests both mass ordering and particle type scaling
- For p_T> 10 GeV/c: no particle type dependence within uncertainties
  - Parton energy loss as hadronization mechanism

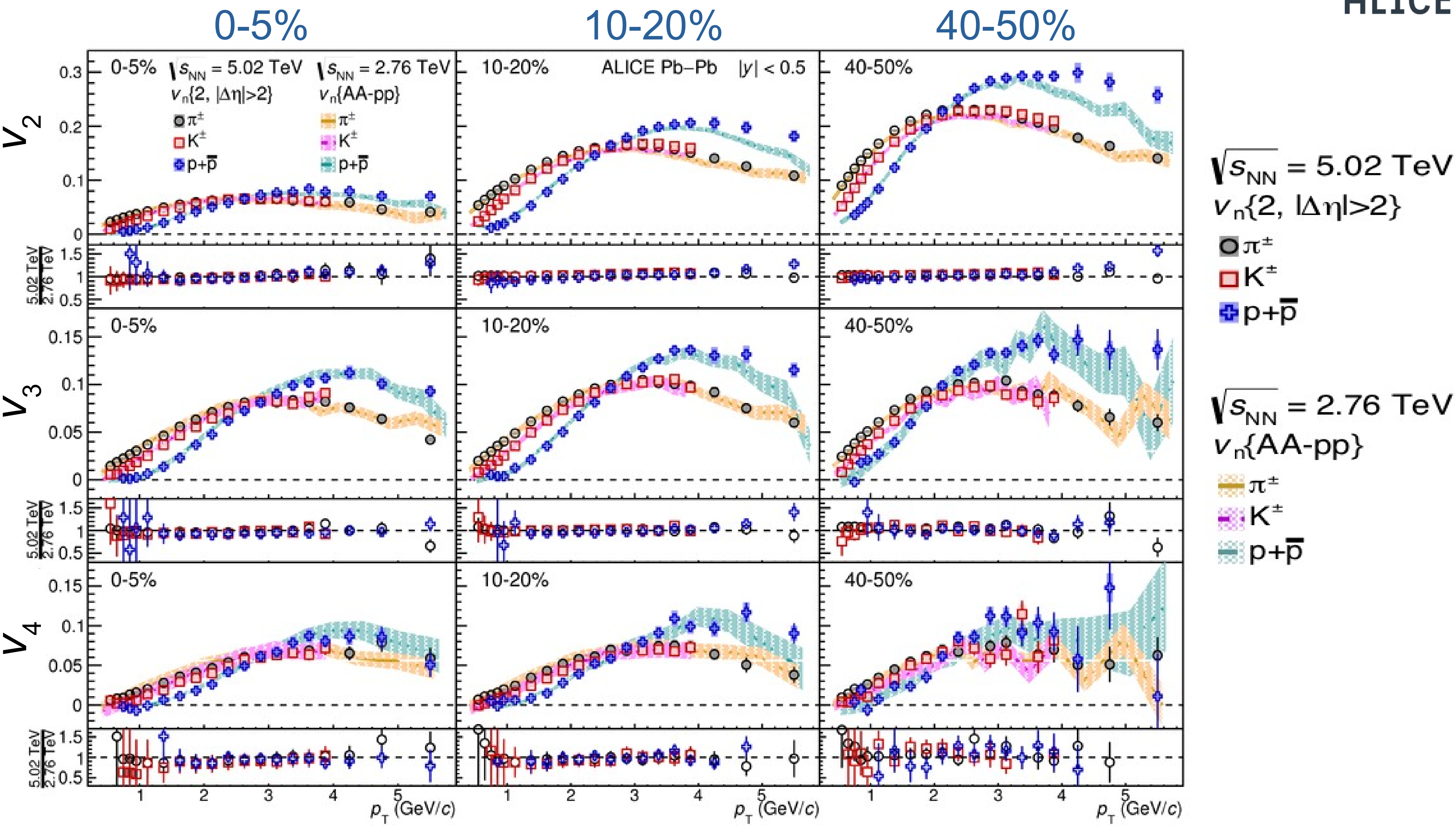
PID $v_n(p_T)$

10-20% ALICE, JHEP 09 (2018) 006 40-50%



- Analogous to the trend of v_2

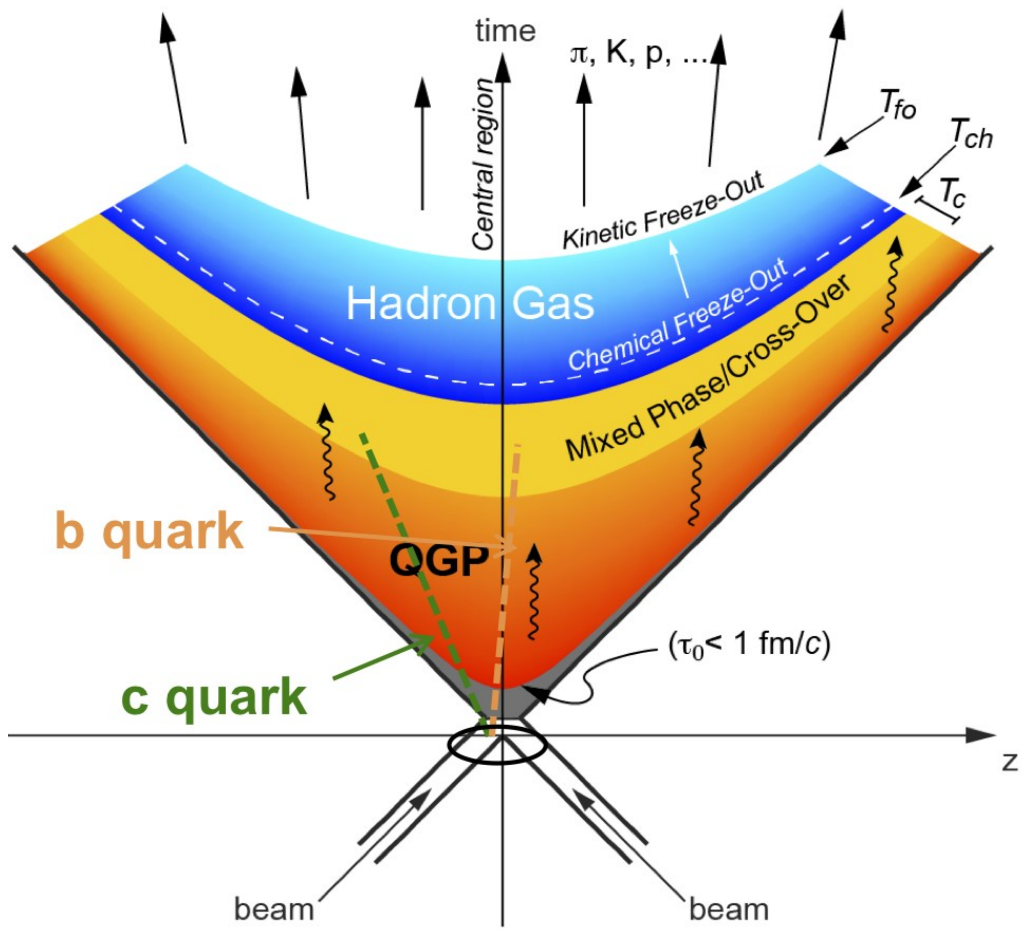
PID $v_n(p_T)$: energy dependence



- Measurements are compatible within uncertainties

ALICE, JHEP 09 (2018) 006
ALICE, JHEP 09 (2016) 164

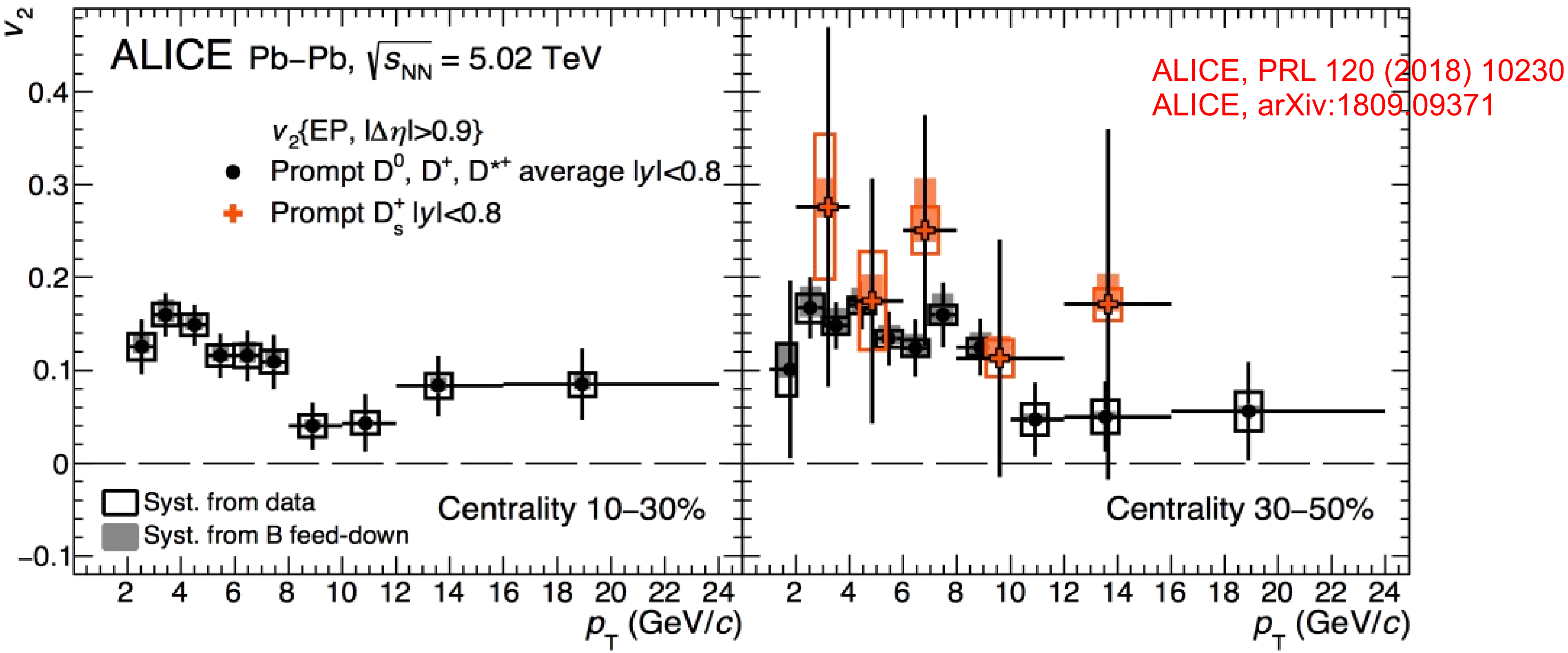
What about heavy quarks?



- Heavy quarks produced early → calculable with perturbative QCD
- Large mass → short formation time → probe the evolution of the QGP
  - $1/2m_c$ (~0.07 fm/*c*) < QGP formation time (~0.1-1 fm/*c*)
- How do they interact with the perfect liquid?

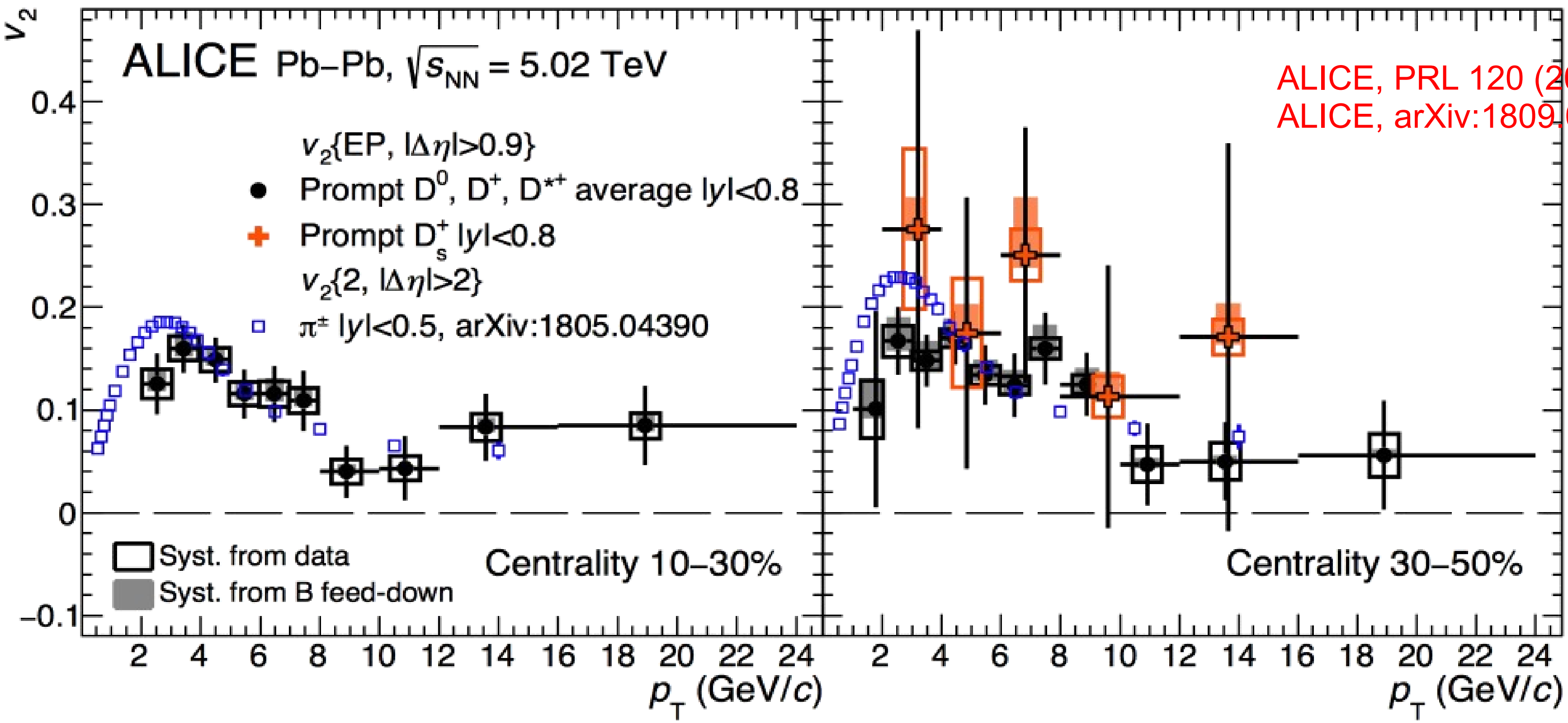
  → v_2 provides a measure of the heavy-quark diffusion

D-meson v_2



- D-meson v_2 larger than 0 in $2<p_T<10$ GeV/c
    - Indication of strong coupling of c-quark to the medium
- First measurement of D$_s$ v_2 at LHC

D-meson v_2

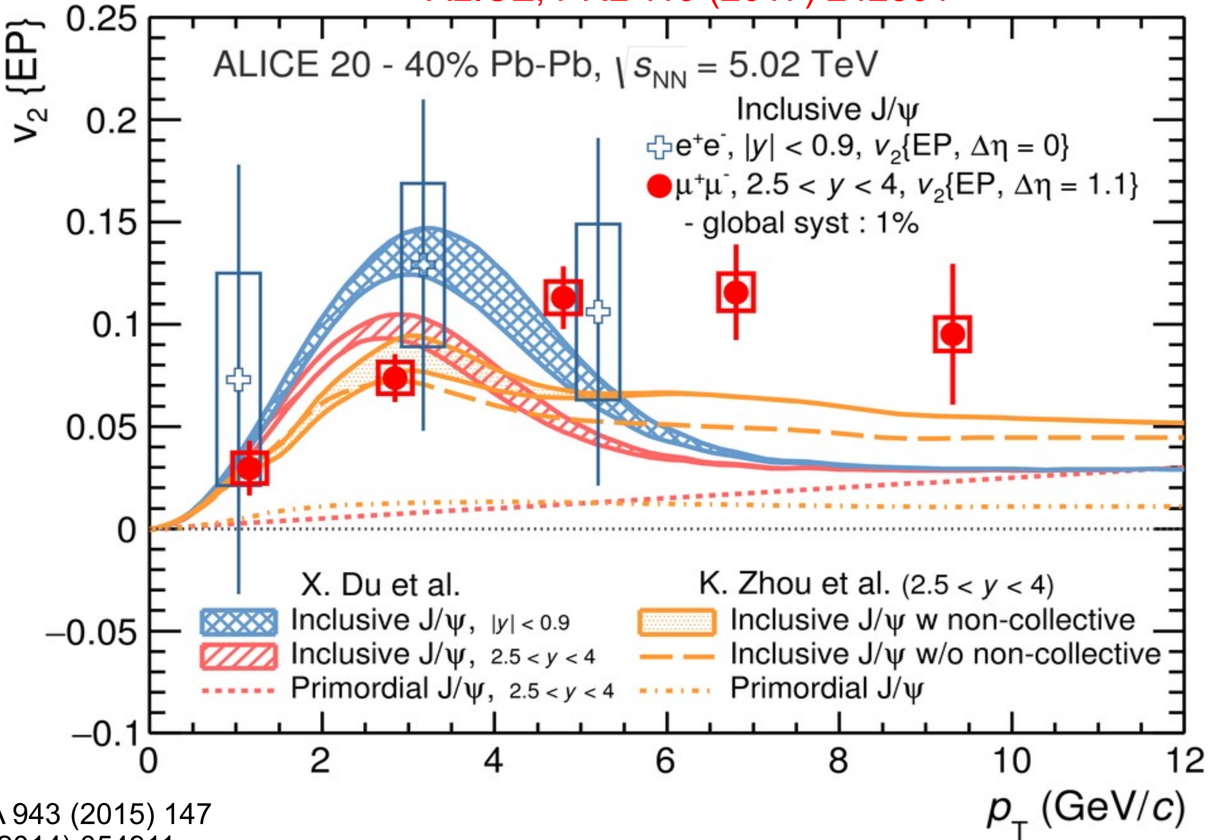


ALICE, PRL 120 (2018) 102301
ALICE, arXiv:1809.09371

- D-meson v_2 larger than 0 in $2<p_T<10$ GeV/c
  - Indication of strong coupling of c-quark to the medium
- First measurement of D_s v_2 at LHC
- D-meson v_2 similar to that of $\pi^{\pm}$
- Is light-quark v_2 responsible for D-meson v_2 (via interactions)?

J/Ψ v_2

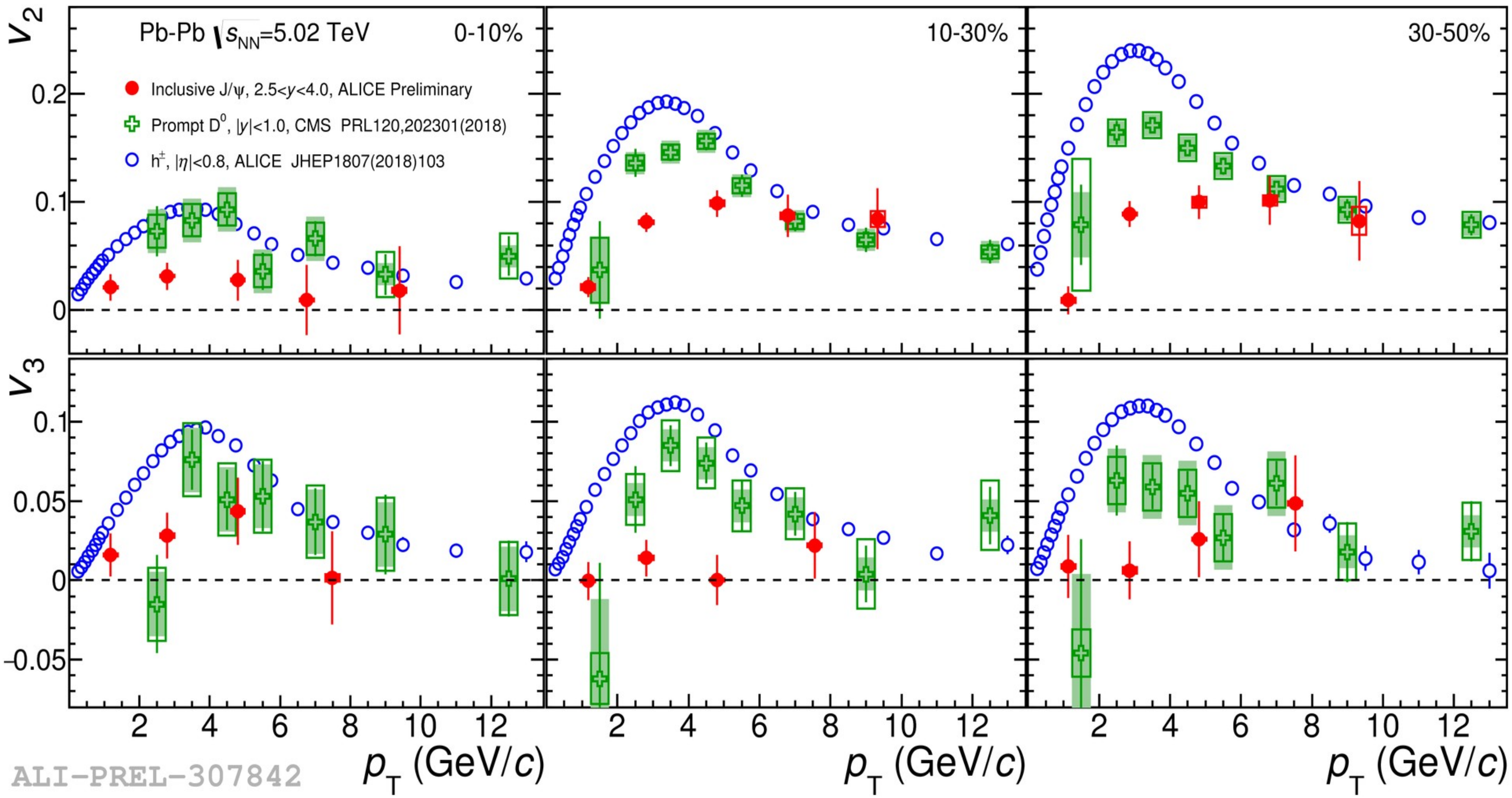
ALICE, PRL 119 (2017) 242301



X. Du and R. Rapp, NPA 943 (2015) 147
K. Zhou et al., PRC 89 (2014) 054911

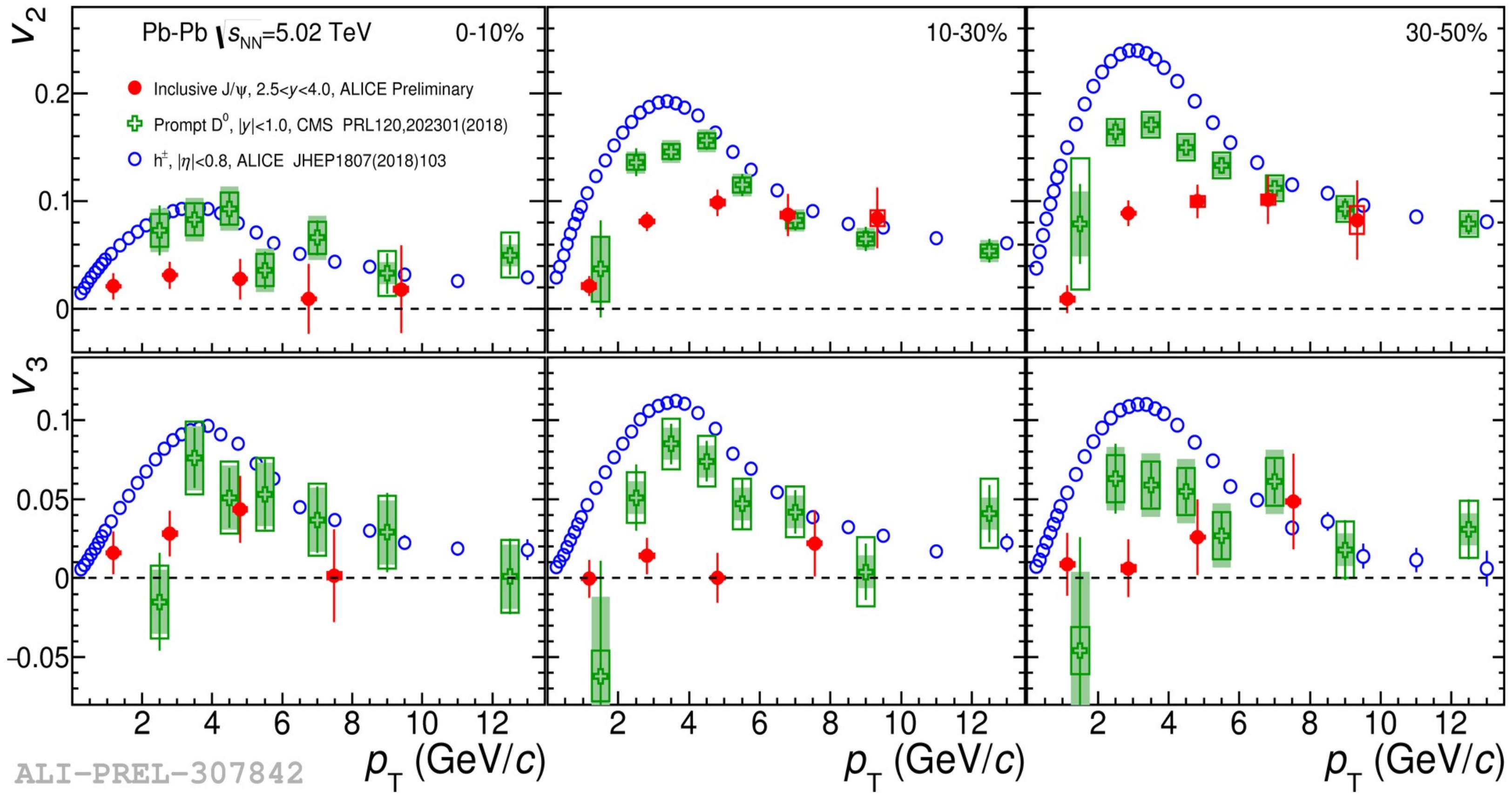
- Significant v_2 is observed in different p_T ranges
- Comparison to transport model calculations
  - Indication of strong coupling of c-quark to the medium

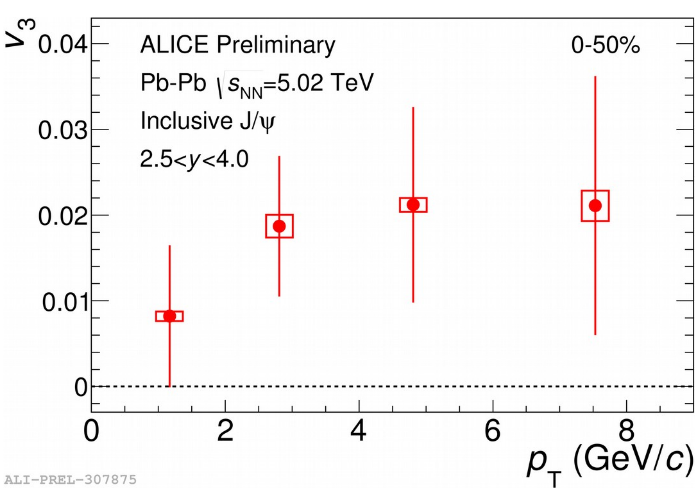
J/Ψ v_n



- Comparison between different flavors
  - Clear ordering for p_T<6 GeV/c: v_n(J/Ψ) < v_n(D^0) < v_n(h$^\pm$)
  - Convergence for p_T>6 GeV/c: v_n(J/Ψ) ≈ v_n(D^0) ≈ v_n(h$^\pm$)

J/Ψ v_n





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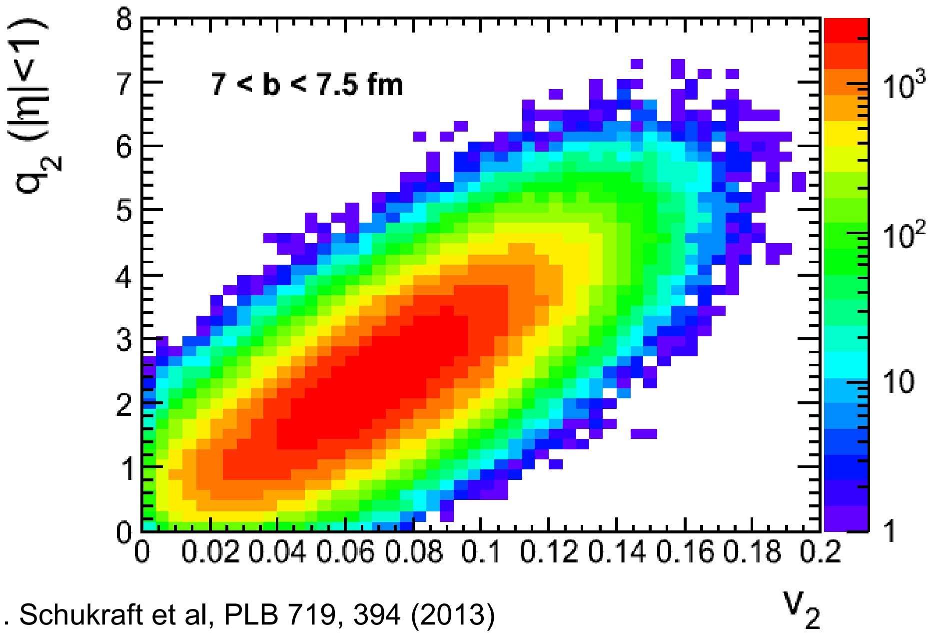
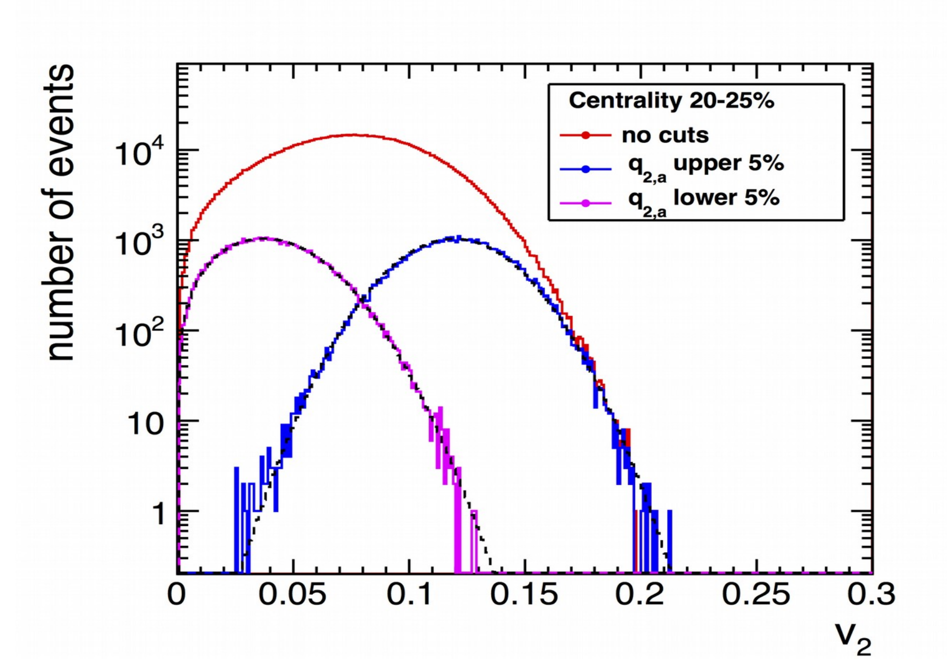
  - Clear ordering for p_T<6 GeV/c: v_n(J/Ψ) < $v_n(D^0)$ < $v_n(h^{\pm})$
  - Convergence for p_T>6 GeV/c: v_n(J/Ψ) ≈ $v_n(D^0)$ ≈ $v_n(h^{\pm})$
- First evidence for v_3(J/Ψ) > 0 (3.7σ significance)

Event Shape Engineering (ESE)





J. Schukraft et al, PLB 719, 394 (2013)
H. Petersen et al, PRC 88, 044918 (2013)
P. Huo et al, PRC 90, 024910 (2014)

Select events with similar centralities (volume) and different shapes based on the event-by-event flow/eccentricity fluctuations

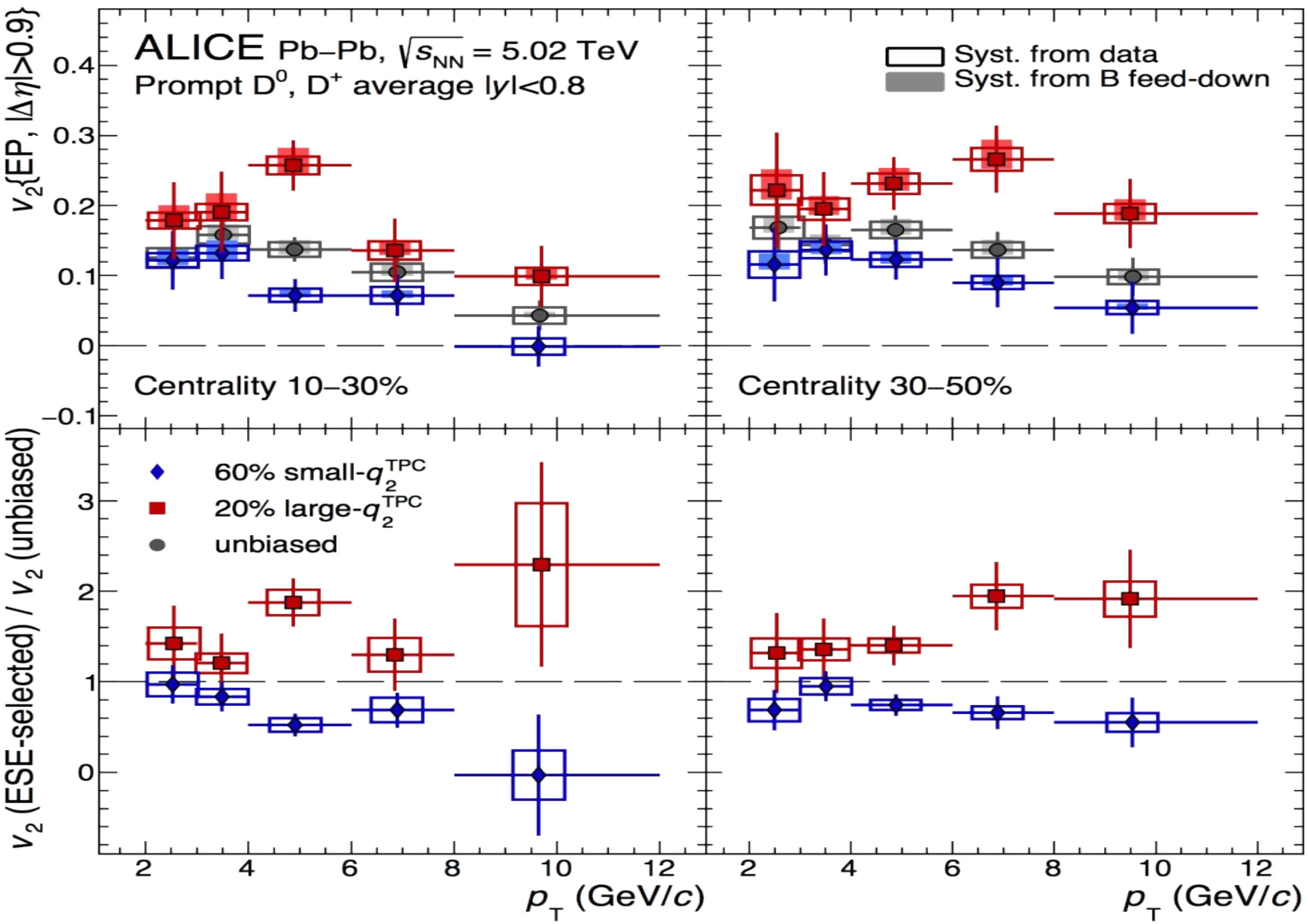
Flow vector → q-distributions

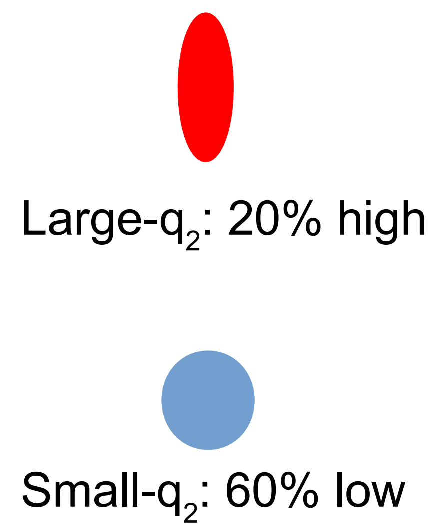
$$Q_{n,x} = \sum_i \cos(n\varphi_i) \qquad Q_{n,y} = \sum_i \sin(n\varphi_i)$$

$$\longrightarrow \quad Q_n = \{Q_{n,x}, iQ_{n,y}\} \qquad q_n = |Q_n| / \sqrt{M}$$

D-meson v_2 with ESE

ALICE, arXiv:1809.09371

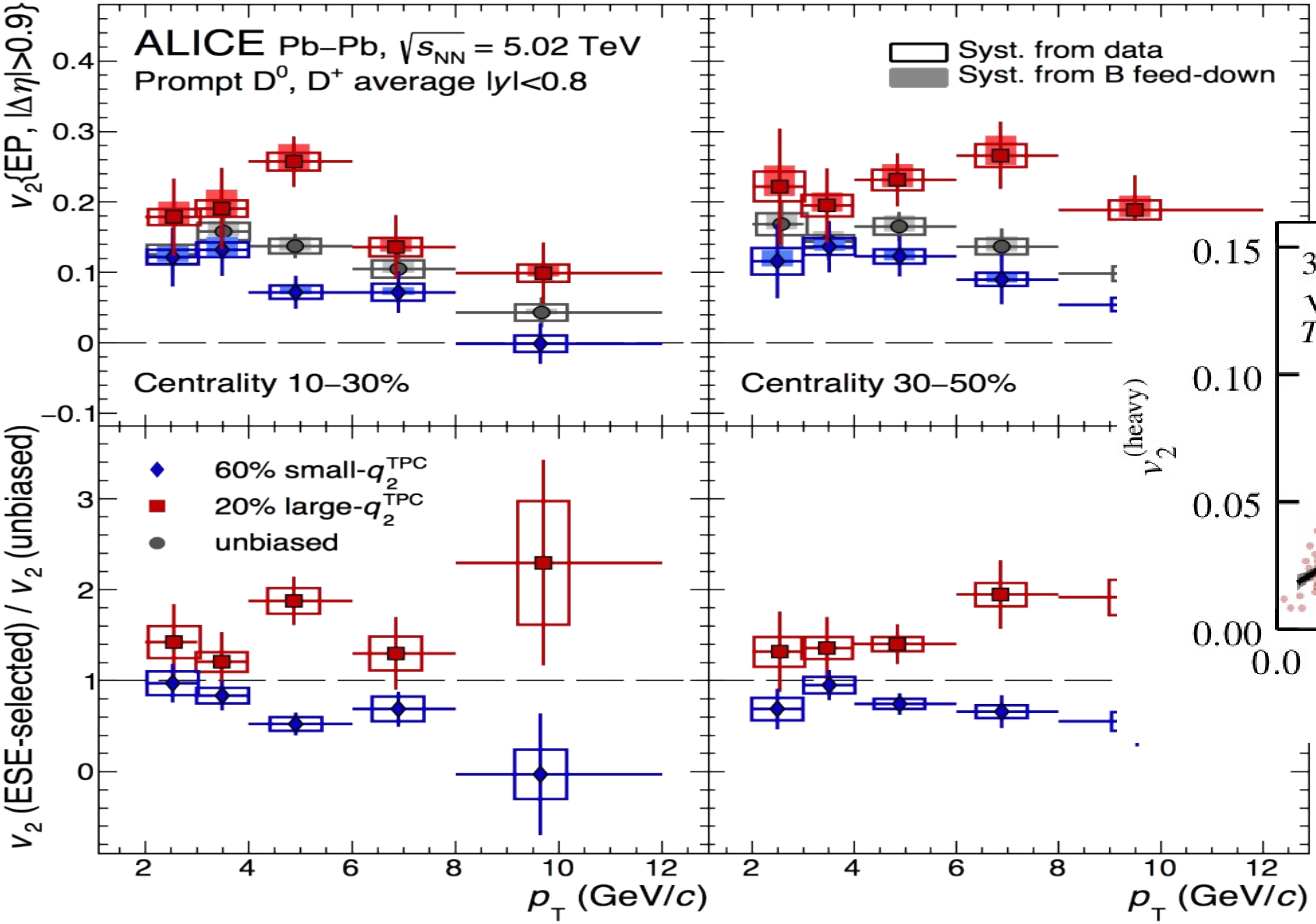




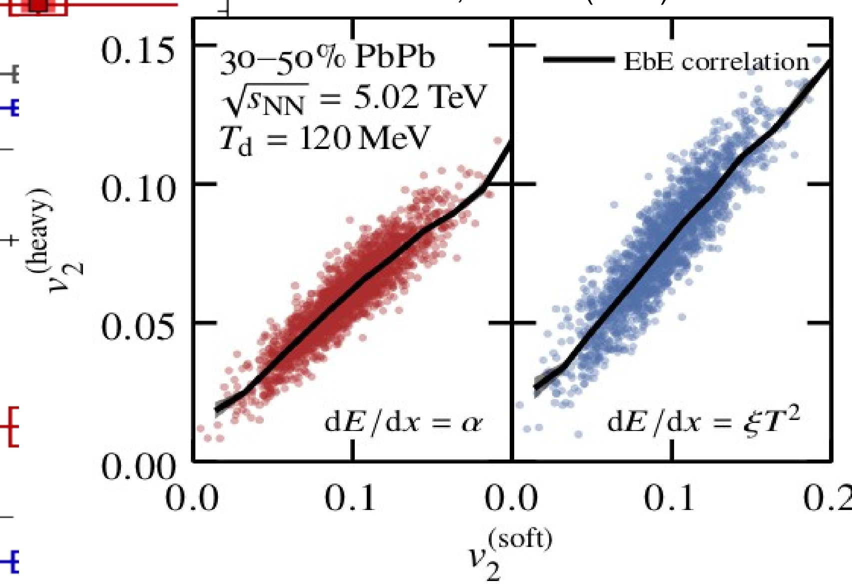
- Correlation between bulk (light charged particles used for ESE) and D-meson v_2
  - Charm sensitive to bulk v_2 and initial state fluctuations

D-meson v_2 with ESE

ALICE, arXiv:1809.09371

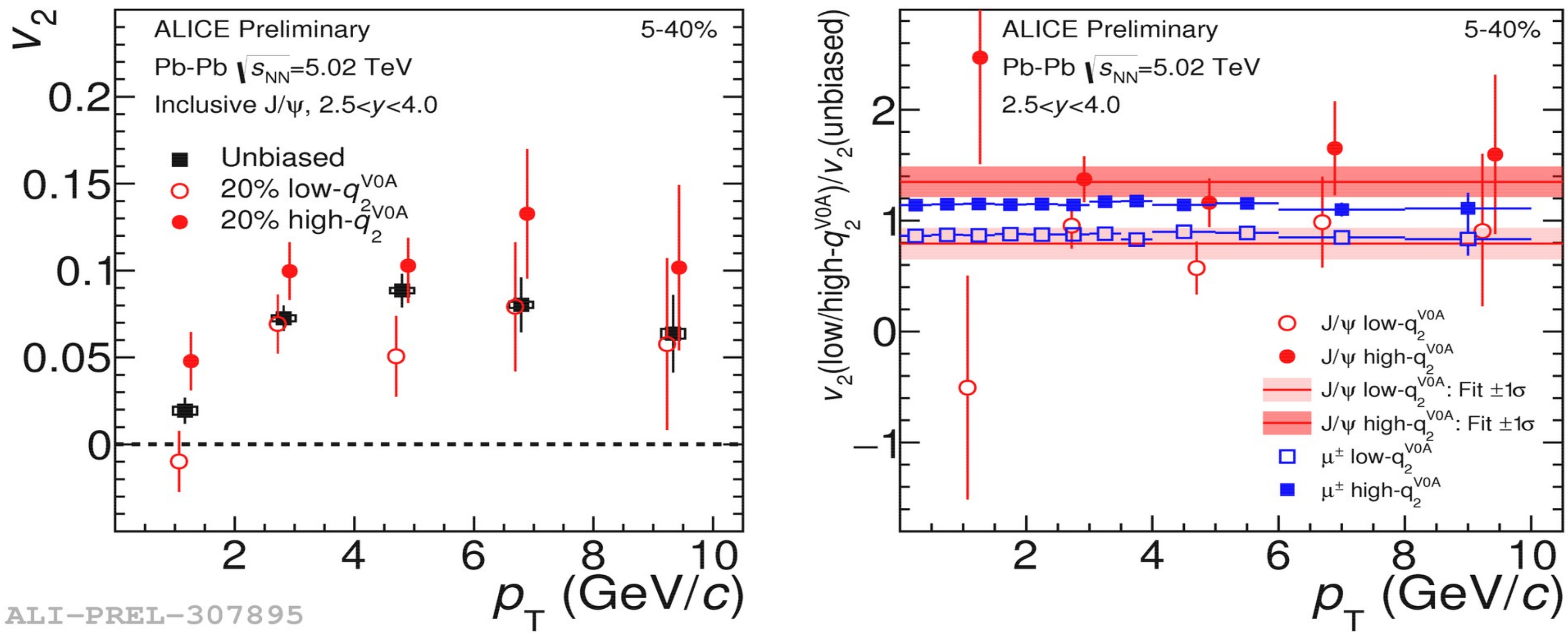


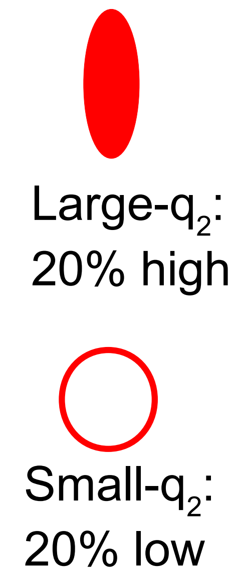
C. Prado et al., PRC 96 (2017) 064903



- Correlation between bulk (light charged particles used for ESE) and D-meson v_2
  - Charm sensitive to bulk v_2 and initial-state fluctuations
- Further constraints on the theory

J/Ψ v_2 with ESE

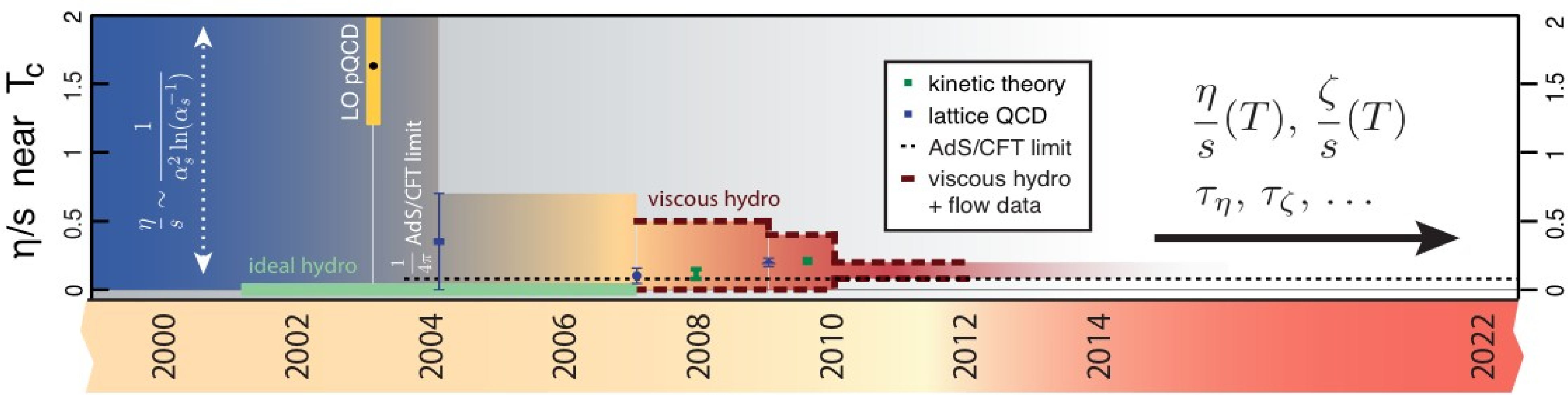




- J/Ψ v_2 is larger or smaller than the average with ESE
- Ratios (ESE/unbiased) of J/Ψ v_2 consistent with those of single muons within uncertainties
  - J/ψ v_2 compatible with the expected variations of the eccentricity

Summary

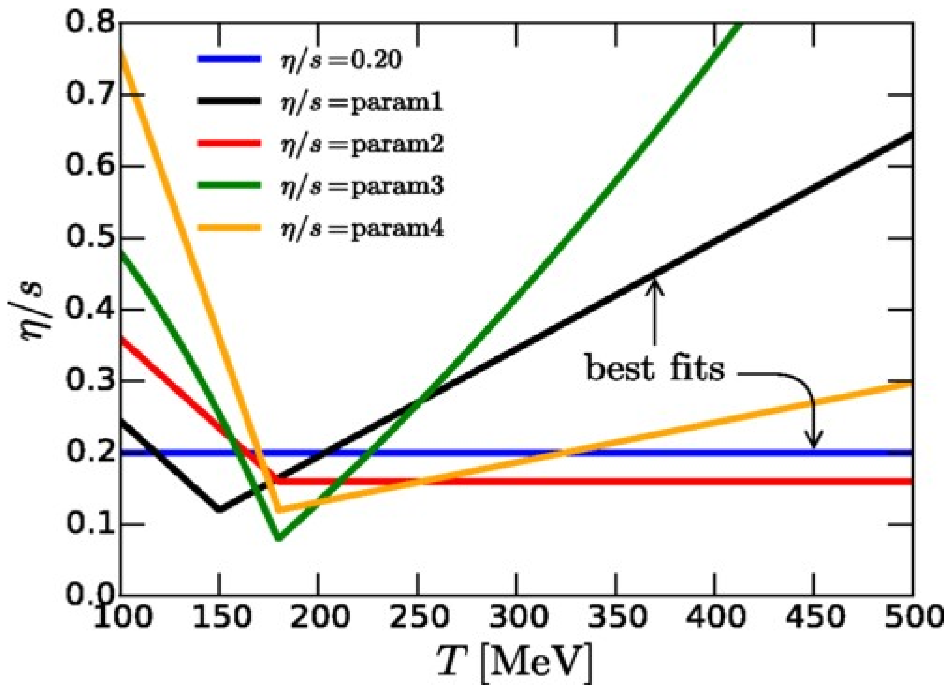
- The properties of the QGP and parts of the QCD phase diagram are understood much better



C. Gale et al, Int. J. Mod. Phys. A 28 (2013) 1340011

Summary

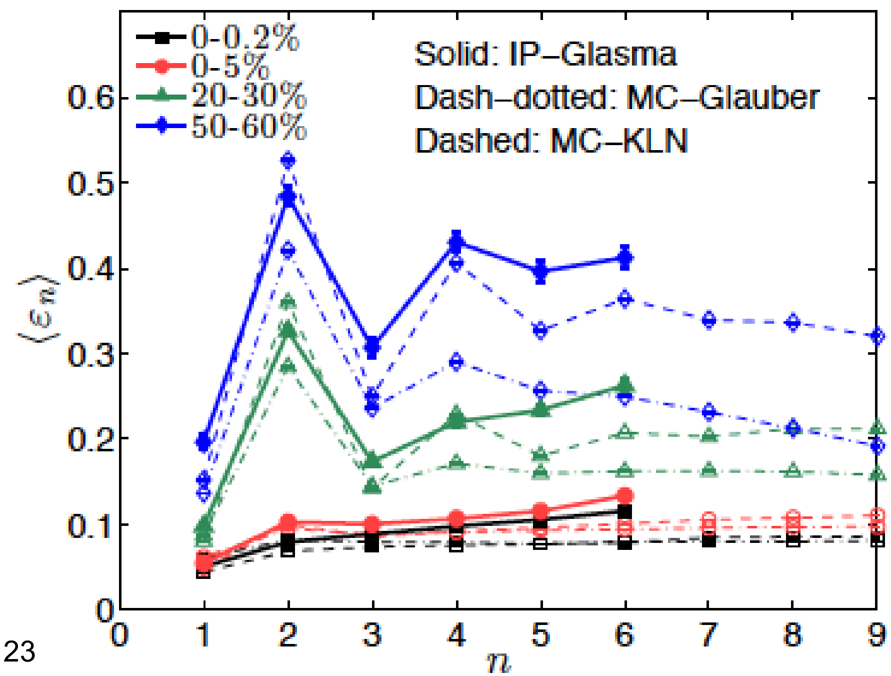
- The properties of the QGP and parts of the QCD phase diagram are understood much better
  - Start constraining using v_n for inclusive and identified particle and their energy dependence
    - Temperature dependence of shear viscosity



H. Niemi et al., PRC 93 (2016) 014912

Summary

- The properties of the QGP and parts of the QCD phase diagram are understood much better
  - Start constraining using v_n for inclusive and identified particle and their energy dependence
    - Temperature dependence of shear viscosity
    - Initial conditions

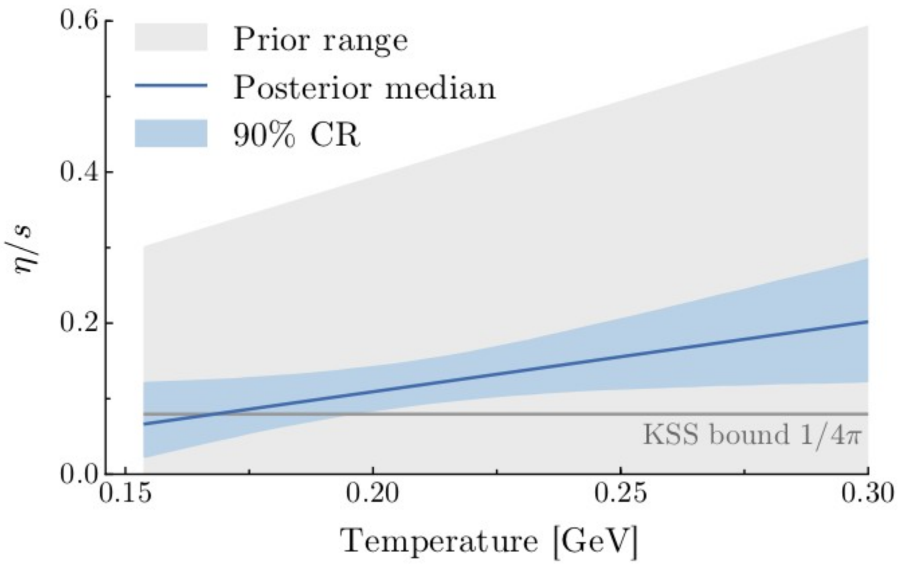


U. Heinz and R. Snellings,
Ann.Rev.Nucl.Part.Sci. 63 (2013) 123

Outlook

- Further constrain temperature dependence of shear viscosity and equation-of-state using Bayesian statistics
- Collectivity in small systems

J. E. Bernhard et al., PRC 94 (2016) 024907



S. Pratt et al., PRL 114 (2015) 202301