Correlation and fluctuations (Theory)

ATHIC2023

Azumi Sakai
Hiroshima University
2023/04/25

ATHIC2023 Correlation and fluctuations

Parallel talks: Monday @ Medium Hall

1. Two-point functions from chiral kinetic theory in magnetized plasma **by L. YANG**
2. Fluctuations and correlations driven by the nuclear structure in relativistic heavy ion collisions **by H. XU**
3. Event-by-event fluctuations of mean transverse momentum in Pb-Pb and Xe-Xe collisions with ALICE **by T. TRIPATHY**
4. Dynamical effects on the phase transition signal **by L. JIANG**

Posters:

F01 Effect of hydrodynamic fluctuations on mixed harmonic cumulants **by C. NONAKA**

F02 Medium effects on two-particle correlations based on the theory of quantum open systems **by M. YAMAMOTO**

F03 Describing Ridge behavior via kinematics between jets and medium **by S. CHO**

F04 The hydrodynamics description of anisotropic flow and flow fluctuations in $\sqrt{s_{NN}}$ = 5.02 TeV Pb-Pb collisions at the LHC **by J. ZHU**

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Fluctuations are everywhere!

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Content

Introduction: Heavy Ion Collisions

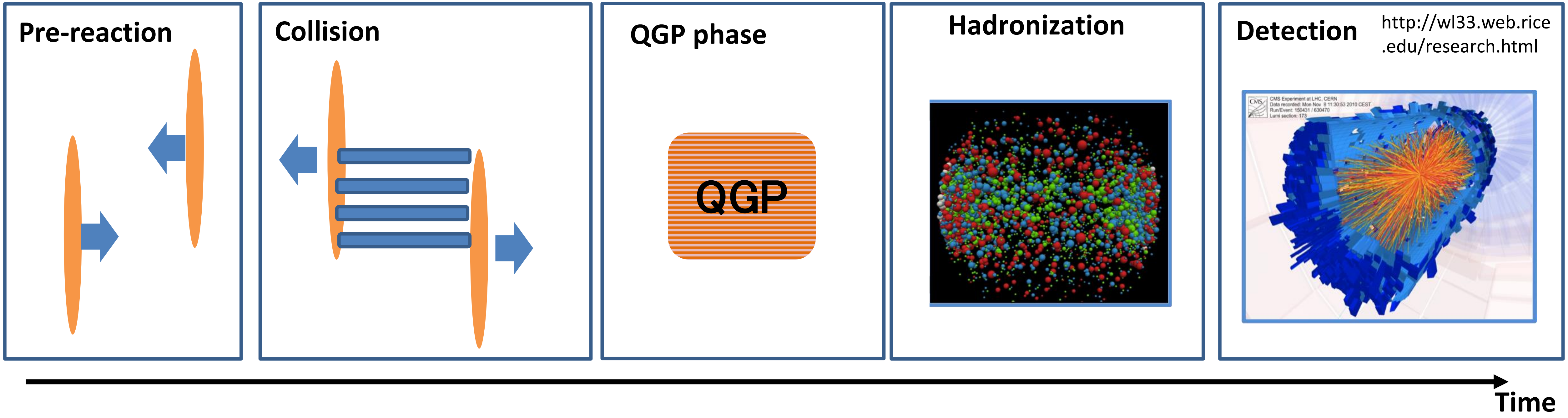
Observables

- Collective flow v_n
- Decorrelation of flow r_n
- Harmonic cumulants

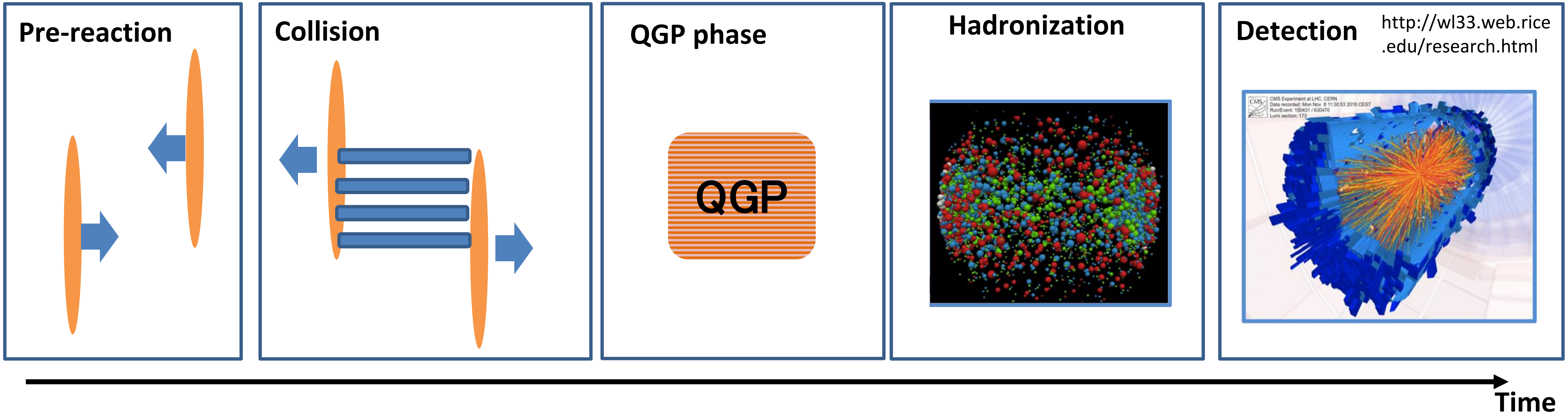
Critical fluctuations

Summary

Space-time evolution of heavy-ion collisions

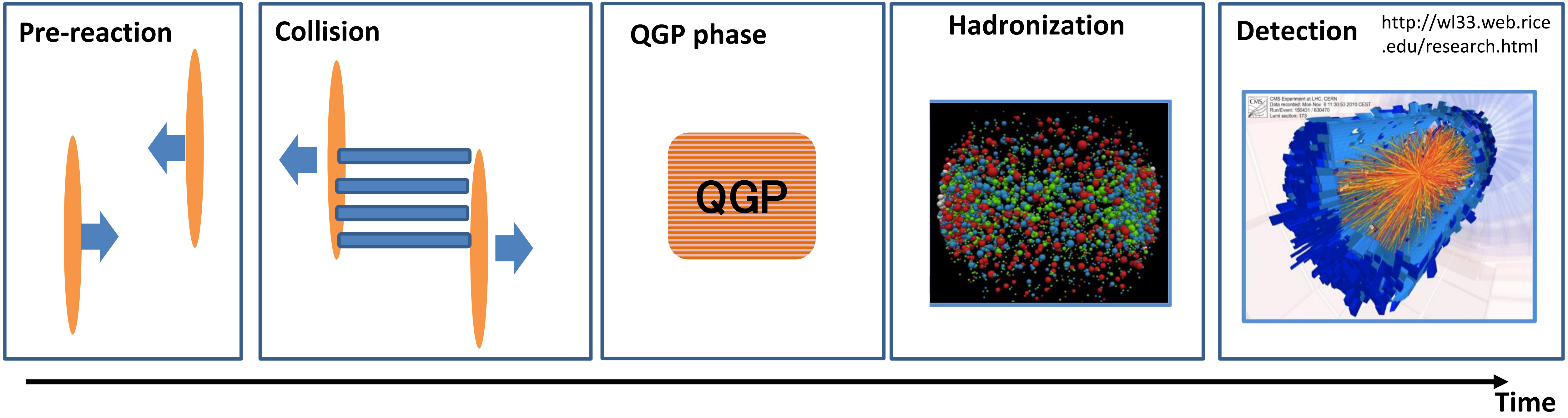


Space-time evolution of heavy-ion collisions



Observables:
- Spectra
- Collective flow
- Anisotropic flow v_n
- Flow correlations

Space-time evolution of heavy-ion collisions



Properties of quark-gluon plasma (QGP)

- Shear and bulk viscosities $\eta/s(T,\mu_B)$, $\zeta/s(T,\mu_B)$
- Equation of state

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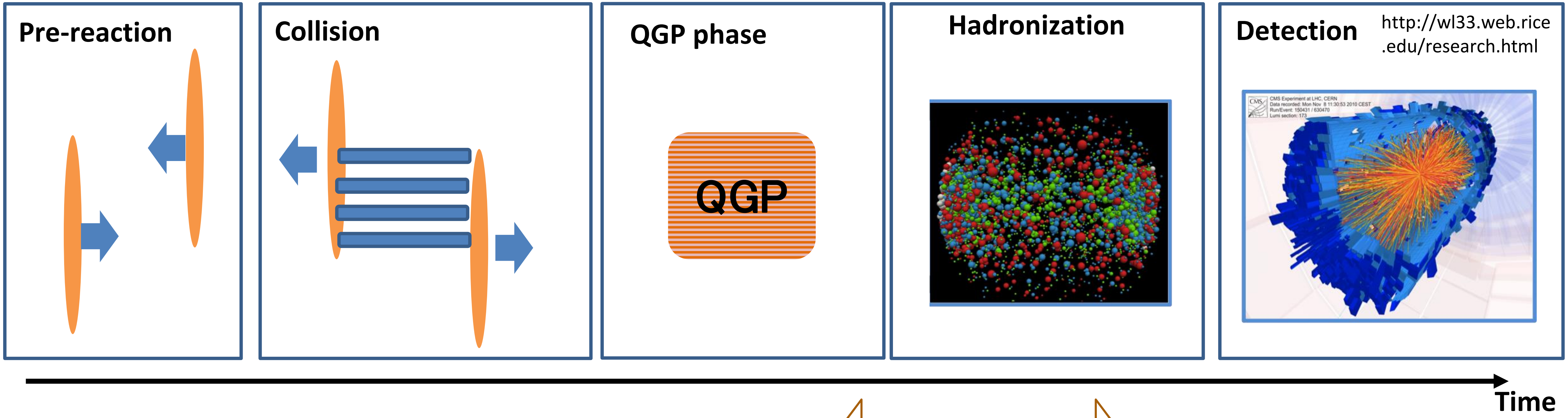
Space-time evolution of heavy-ion collisions



Properties of quark-gluon plasma (QGP)

- Shear and bulk viscosities $\eta/s(T,\mu_B), \zeta/s(T,\mu_B)$
- Equation of state

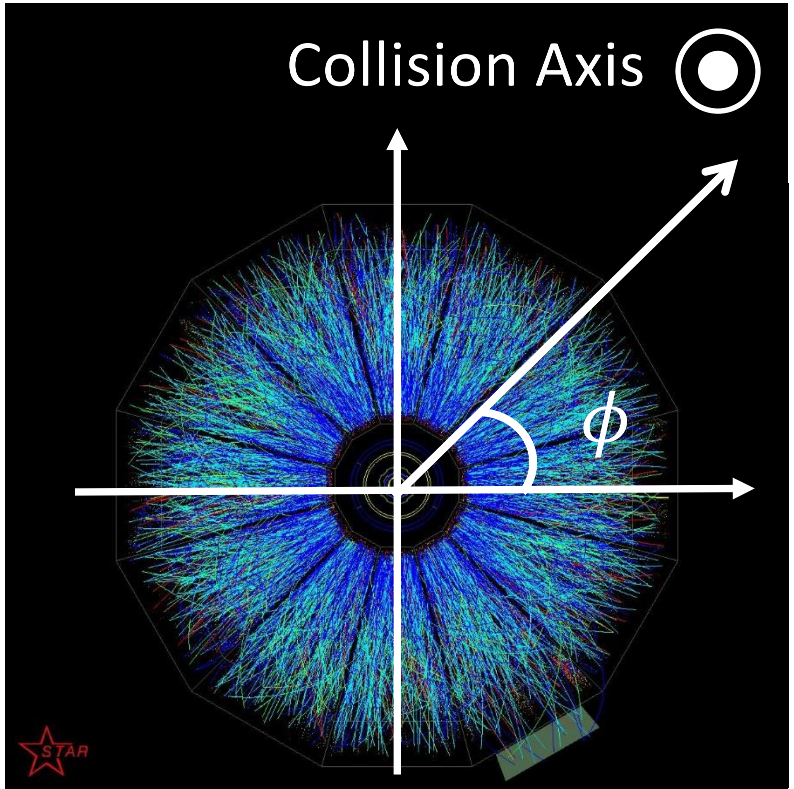
Dynamical model

Initial condition
Hydrodynamics
Hadron cascade

Observables:

- Spectra
- Collective flow
- Anisotropic flow v_n
- Flow correlations

Collective flow



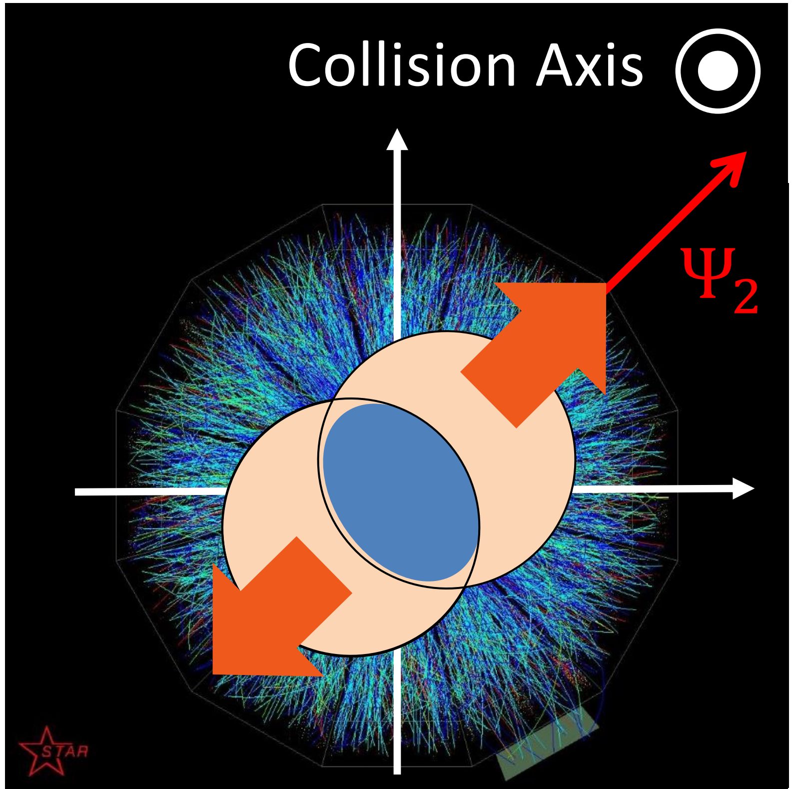
https://www.zmescience.com/science/physics/quark-gluon-plasma-lhc-26052011/

Single particle distribution

$$\frac{dN}{d\phi} = \frac{N}{2\pi}\left[1 + 2\sum_{n=1}^{\infty} v_n \cos n(\phi - \Psi_n)\right]$$

v_n : Anisotropic flow
ϕ : Azimuthal angle of particle
Ψ_n: Event plane angle

Collective flow



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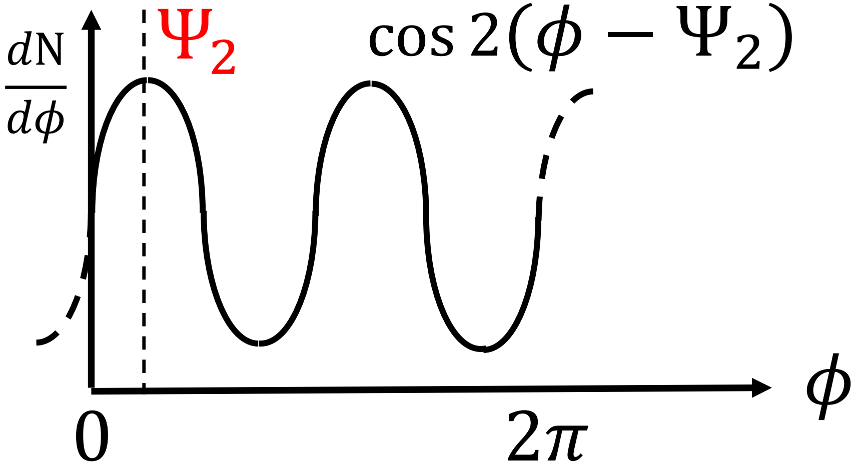
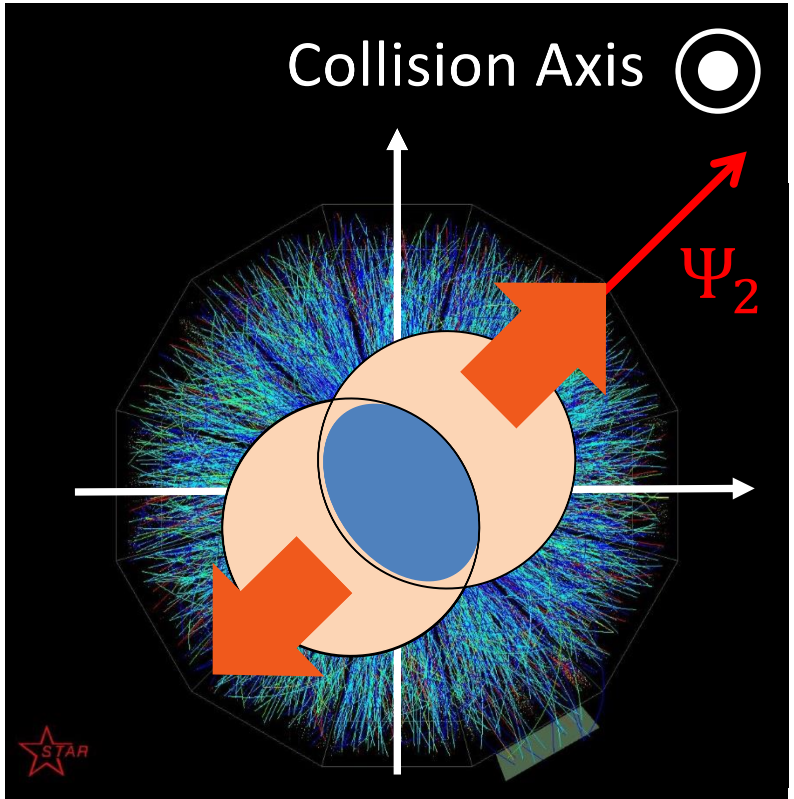


Hydrodynamic picture:
Pressure gradient → Large elliptic flow v_2

Collective flow



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Particle pair distribution

$$\frac{dN_{\text{pair}}}{d\Delta\phi} = \frac{N_{\text{pair}}}{2\pi}\left[1 + 2\sum V_{n\Delta}\cos(n\Delta\phi)\right]$$

→ Correlation of anisotropic flow

Decorrelation of anisotropic flow

2013: Decorrelation – transverse plane: $r_n\left(p_T^a, p_T^b\right)$ proposed

2015: Decorrelation measured in Pb + Pb collisions 2.76 TeV

$r_n\left(p_T^a, p_T^b\right) < 1, r_n\left(\eta_p^a, \eta_p^b\right) < 1$ Decorrelation observed!

2020: Decorrelation measured in Xe+Xe collisions

Nuclear deformation

Decorrelation measured in Isobar collisions

G. Yan @Parallel A
Mon. 15:00

Decorrelation of anisotropic flow

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Decorrelation measured in Isobar collisions

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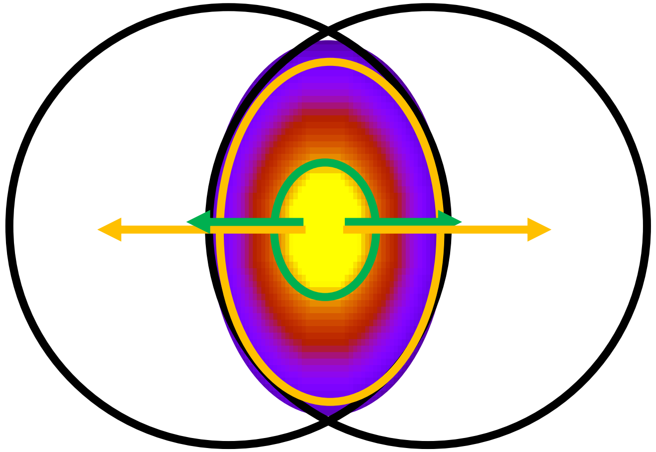
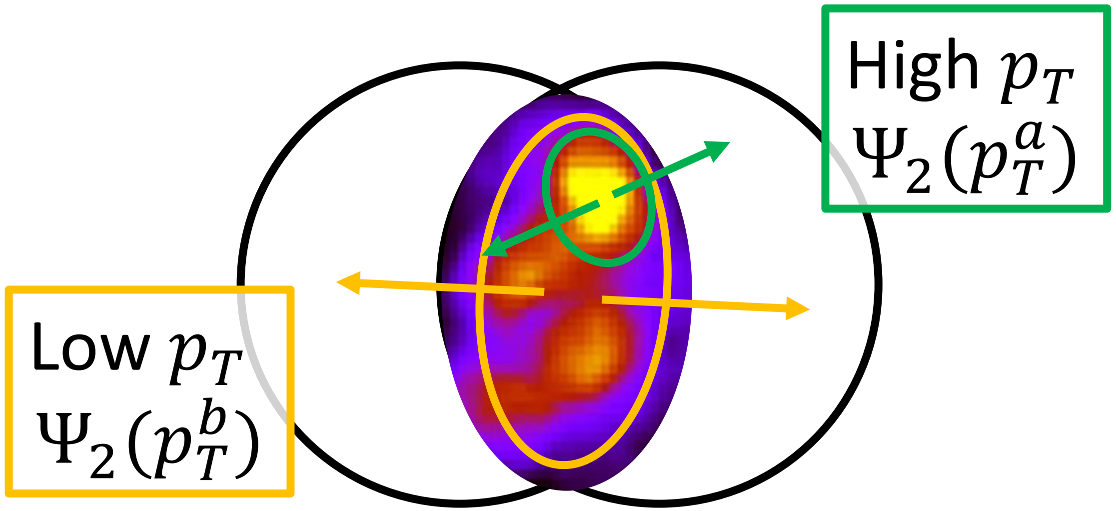
Decorrelation have been a hot topic!

Decorrelation - transverse

Particle pair distribution $\frac{dN_{\text{pair}}}{d\Delta\phi} = \frac{N_{\text{pair}}}{2\pi}\left[1 + 2\sum V_{n\Delta}\cos(n\Delta\phi)\right]$





$\Psi_2(p_T^a) = \Psi_2(p_T^b)$

$V_{n\Delta}(p_T^a, p_T^b) = v_n(p_T^a)v_n(p_T^b)$

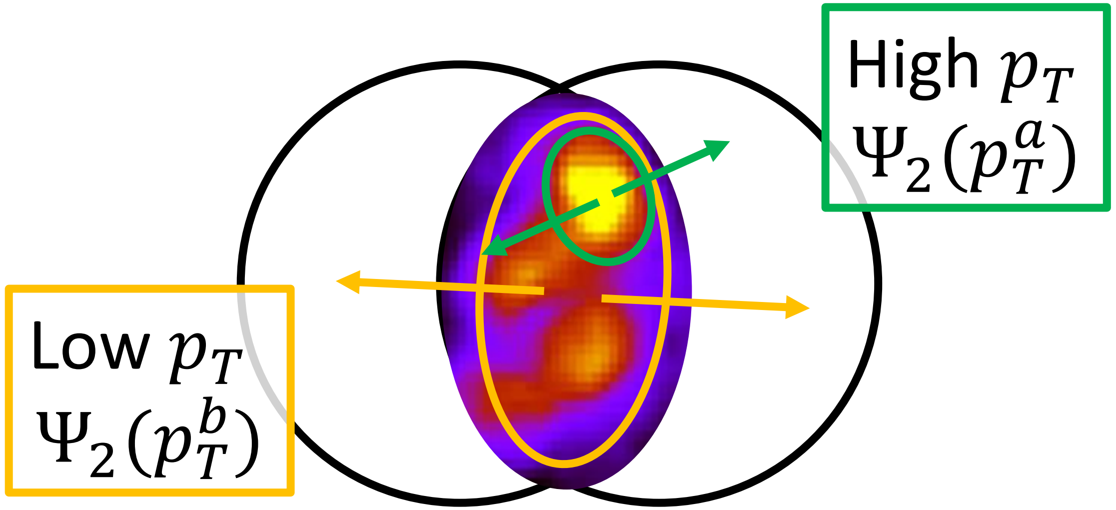
$\Psi_2(p_T^a) \neq \Psi_2(p_T^b)$ Event plane decorrelation

$V_{n\Delta}(p_T^a, p_T^b) \neq v_n(p_T^a)v_n(p_T^b)$ Factorization breaking

Decorrelation - transverse

Factorization ratio

$$r_n(p_T^a, p_T^b) \equiv \frac{V_{n\Delta}(p_T^a, p_T^b)}{\sqrt{V_{n\Delta}(p_T^a, p_T^a)V_{n\Delta}(p_T^b, p_T^b)}}$$



$\Psi_2(p_T^a) = \Psi_2(p_T^b)$

$V_{n\Delta}(p_T^a, p_T^b) = v_n(p_T^a)v_n(p_T^b)$

$r_n(p_T^a, p_T^b) \sim 1$

Unique event plane

$\Psi_2(p_T^a) \neq \Psi_2(p_T^b)$

$V_{n\Delta}(p_T^a, p_T^b) \neq v_n(p_T^a)v_n(p_T^b)$

$r_n(p_T^a, p_T^b) < 1$

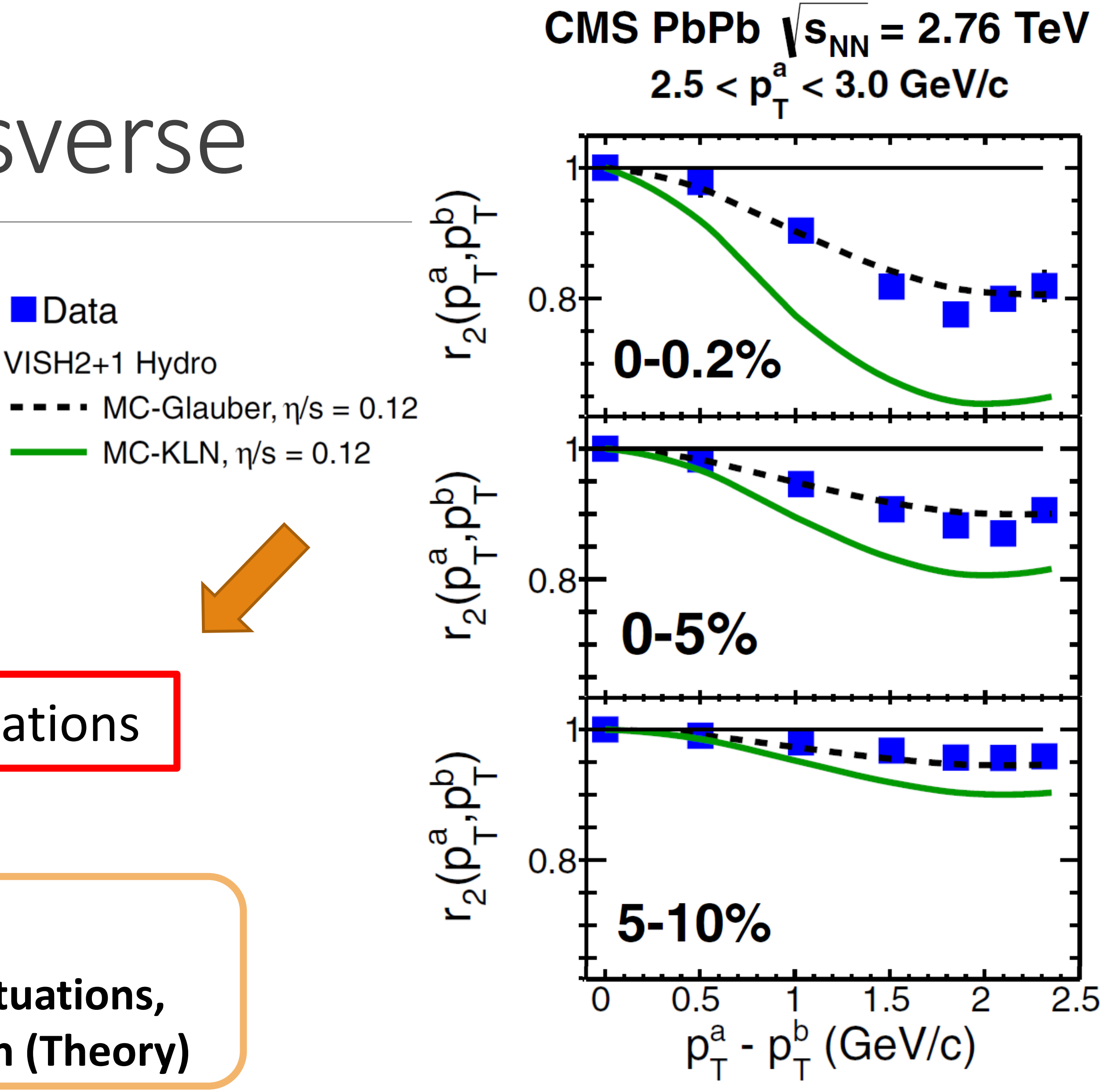
Event plane decorrelation

F.G. Gardim *et al.*, Phys. Rev . C 87, 031901 (2013)
CMS Collaboration, Phys. Rev. C 92, 034911 (2015)

Decorrelation - transverse

Factorization ratio

$$r_n(p_T^a, p_T^b) \equiv \frac{V_{n\Delta}(p_T^a, p_T^b)}{\sqrt{V_{n\Delta}(p_T^a, p_T^a)V_{n\Delta}(p_T^b, p_T^b)}}$$



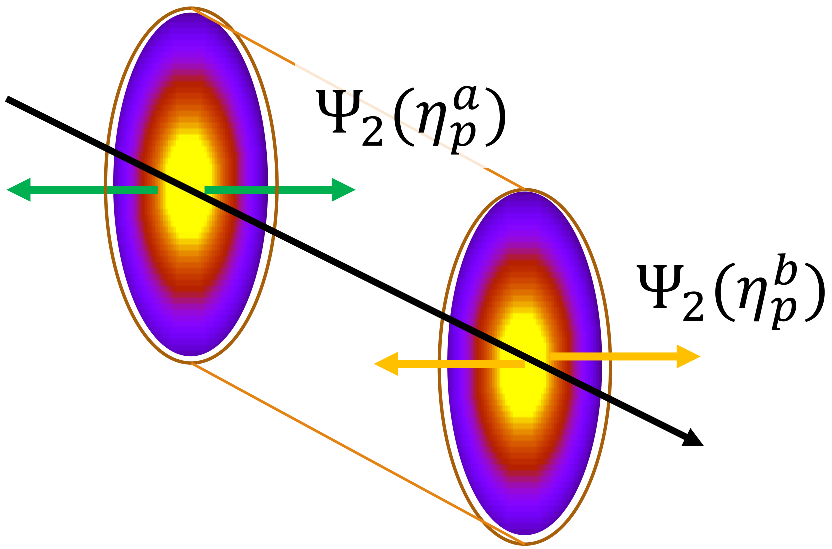
$r_2(p_T^a, p_T^b)$ sensitive to initial state fluctuations

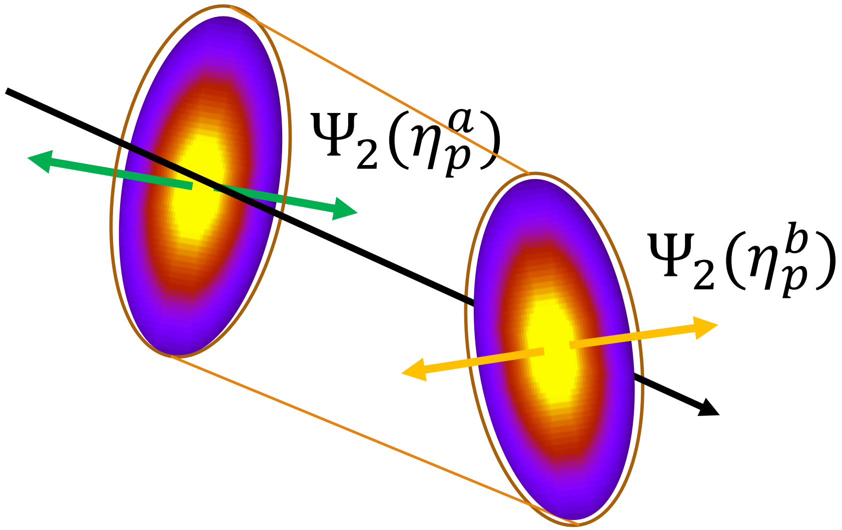
CMS Collaboration, Phys. Rev. C 92, 034911 (2015)

J. Zhu @Poster F04

Hydrodynamic studies on flow, flow fluctuations, and transverse momentum decorrelation (Theory)

Decorrelation - longitudinal





Anisotropic flow v_n,

Event plane angle Ψ_n

η_p dependence?

Event-by-event fluctuations:

$$v_n(\eta_1) \neq v_n(\eta_2)$$
$$\Psi_n(\eta_1) \neq \Psi_n(\eta_2)$$

$$\Psi_2(\eta_p^a) = \Psi_2(\eta_p^b)$$
$$V_{n\Delta}(\eta_p^a, \eta_p^b) = v_n(\eta_p^a) v_n(\eta_p^b)$$

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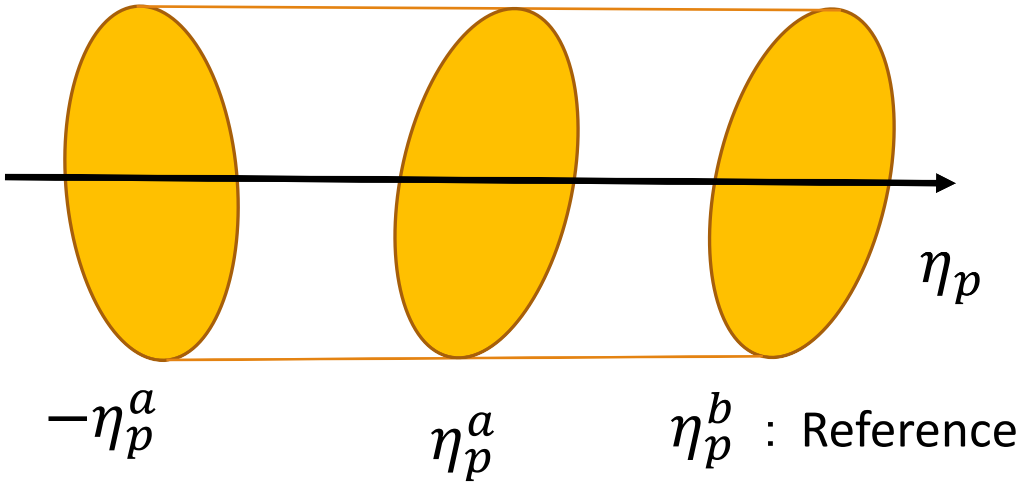
$$V_{n\Delta}(\eta_p^a, \eta_p^b) \neq v_n(\eta_p^a) v_n(\eta_p^b)$$

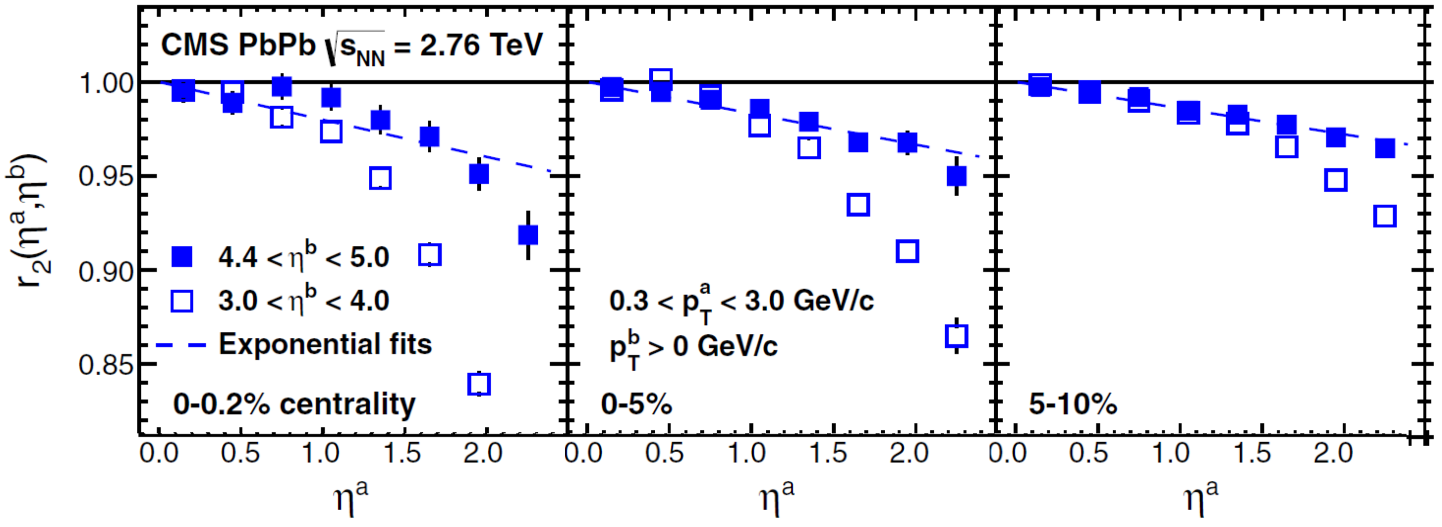
Event plane decorrelation

Factorization breaking

Decorrelation - longitudinal



Correlation?



CMS Collaboration, Phys. Rev. C 92, 034911 (2015)

$$r_n(\eta_p^a,\eta_p^b) = \frac{V_{n\Delta}(-\eta_p^a,\eta_p^b)}{V_{n\Delta}(\eta_p^a,\eta_p^b)},\quad V_{n\Delta} = \langle\cos(n\Delta\phi)\rangle$$

$$r_n(\eta_p^a,\eta_p^b) < 1$$

Decorrelation observed!

$$r_n(\eta_p^a,\eta_p^b)\sim 1$$

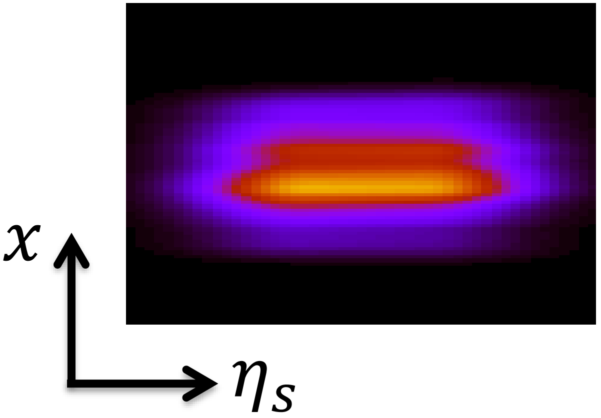
Unique event plane

$$r_n(\eta_p^a,\eta_p^b) < 1$$

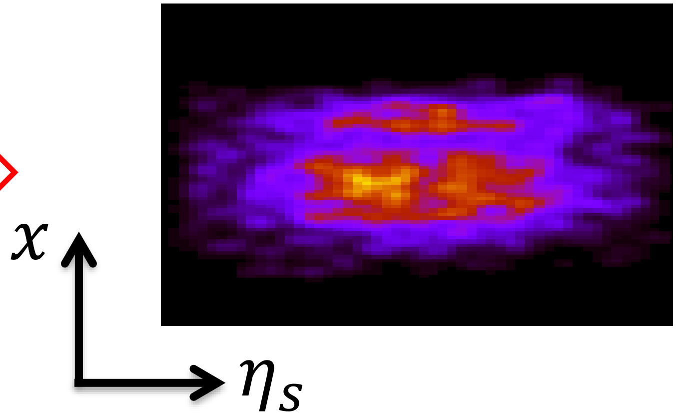
Decorrelation

Constraints on 3D initial condition

Longitudinal fluctuations (Theory)



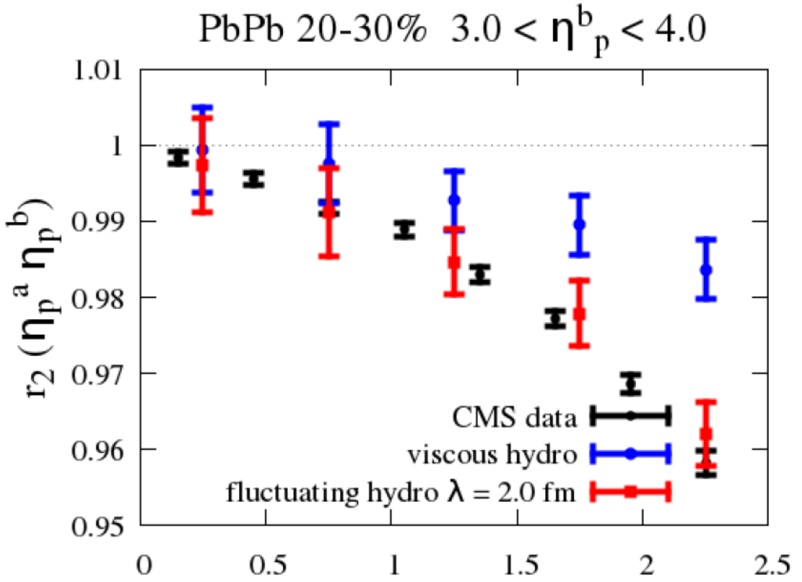
Initial longitudinal fluctuations



+

Hydrodynamic fluctuations

$$\pi_{\mu\nu} = 2\eta\Delta^{\mu\nu}_{\alpha\beta}\partial^{\alpha}u^{\beta} + \xi^{\mu\nu}$$

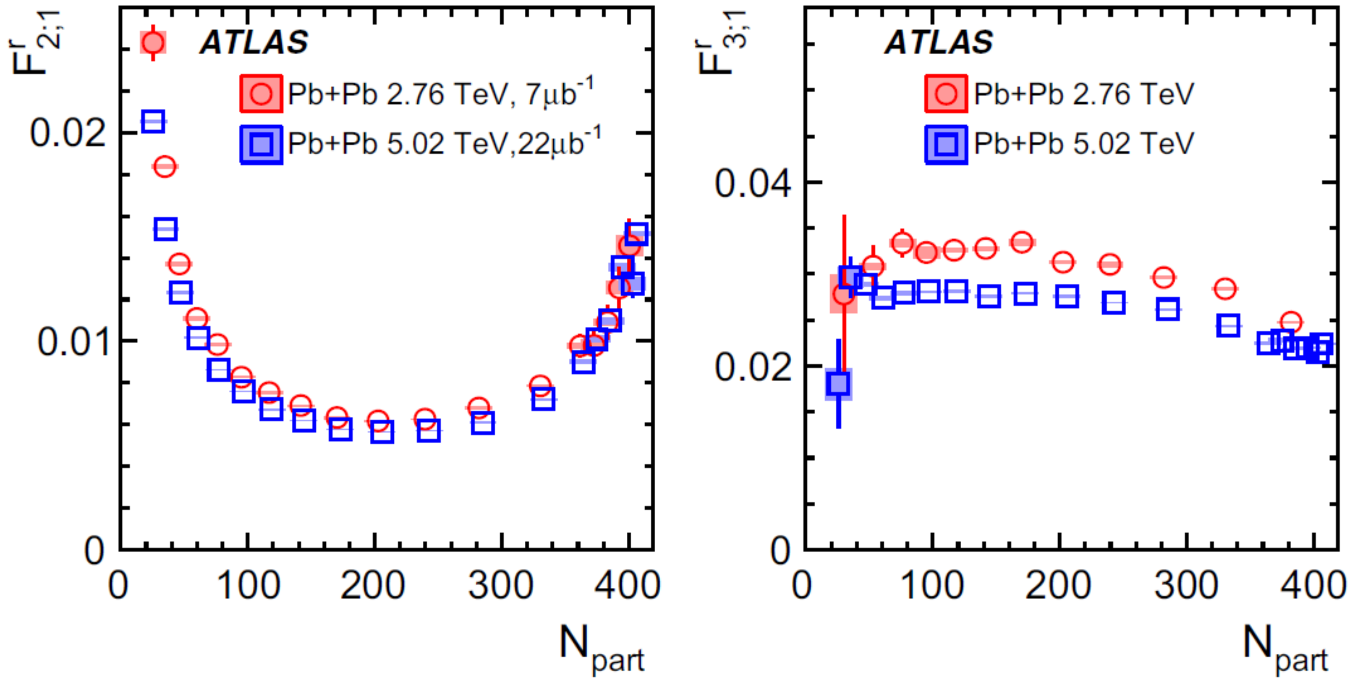


AS *et al.*, PLB 829 (2022) 137053

Centrality dependence of r_n

$r_n(\eta) \equiv 1 - 2F^r_{n;k}\eta$

$F^r_{n;k}$: Slope of r_n



ATLAS Collaboration, ATLAS-CONF-2017-003.

F_2: Centrality dependence

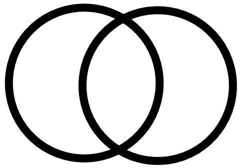
F_3: No centrality dependence
→ Fluctuations

Centrality dependence of r_n

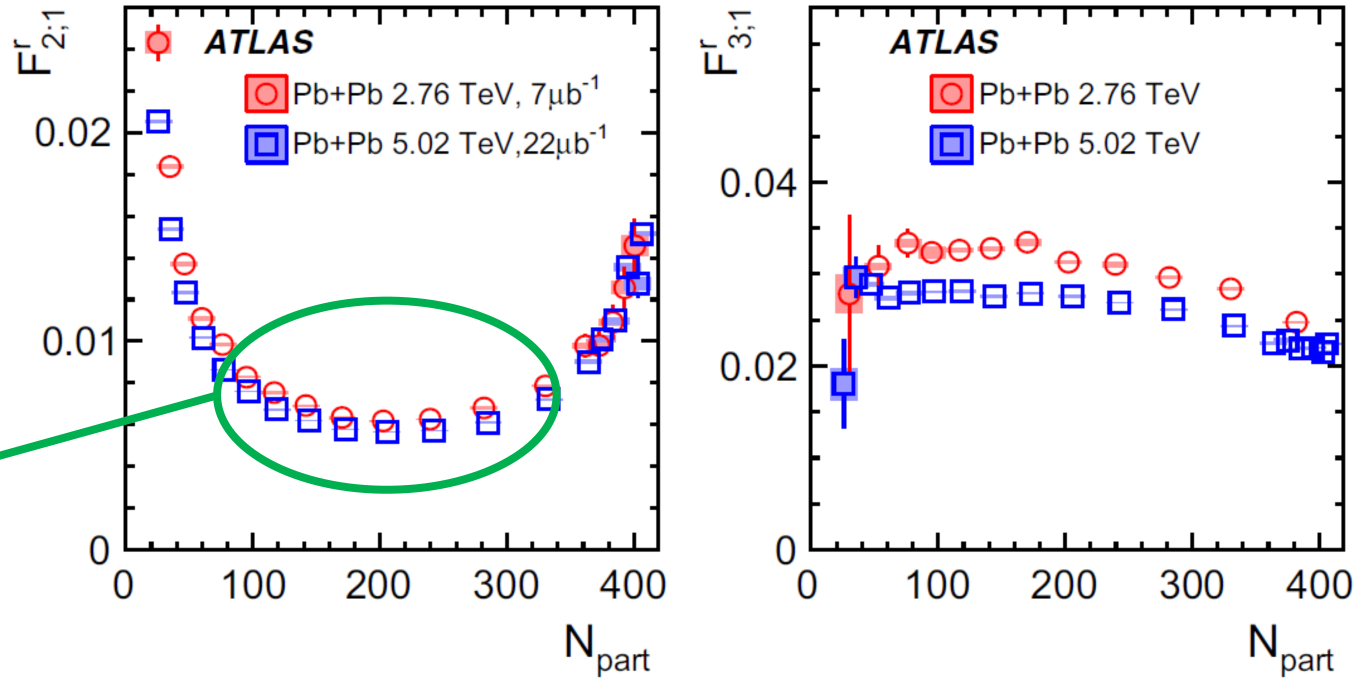
$$r_n(\eta) \equiv 1 - 2F^r_{n;k}\eta$$

$F^r_{n;k}$: Slope of r_n

v_2 dominated by initial geometry



Initial elliptic geometry
→ Stabilized event plane
→ F_2 decrease



ATLAS Collaboration, ATLAS-CONF-2017-003.

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Centrality dependence of r_n

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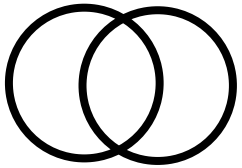
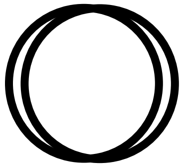
$F^r_{n;k}$: Slope of r_n

v_2 dominated by initial geometry

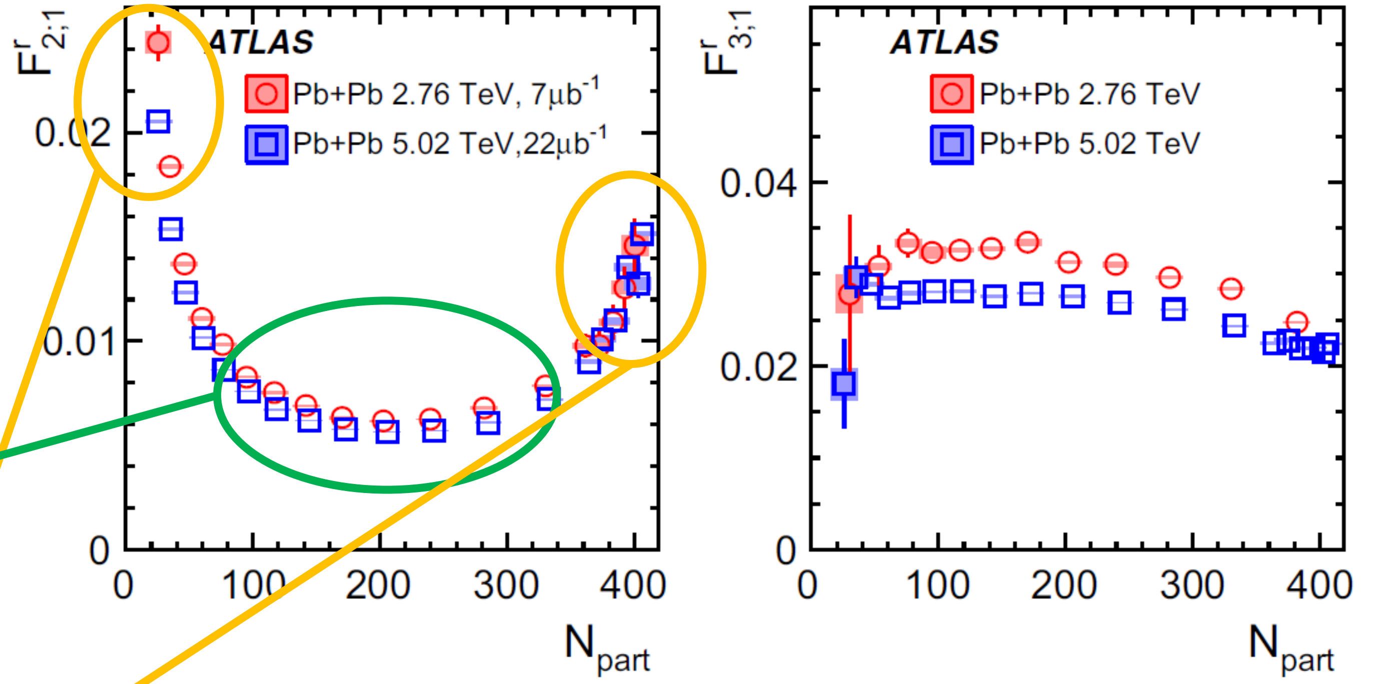


Initial elliptic geometry
→ Stabilized event plane
→ F_2 decrease

v_2 dominated by fluctuations



Event plane less stabilized

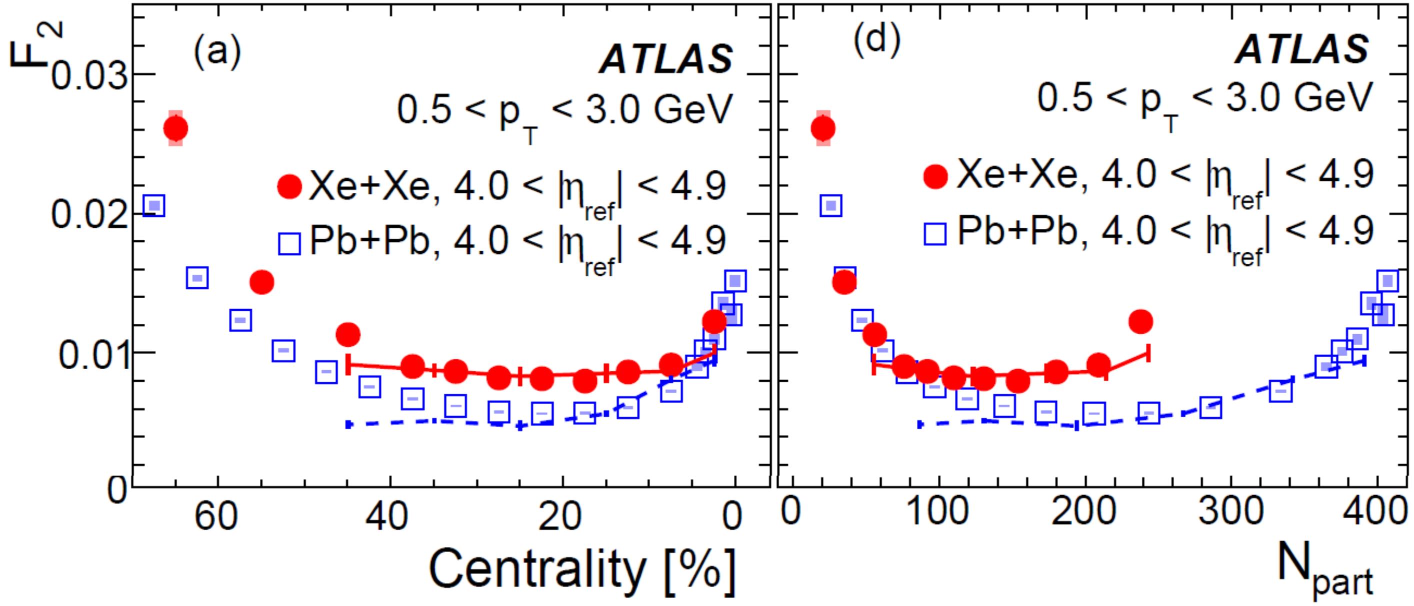


ATLAS Collaboration, ATLAS-CONF-2017-003.

F_2: Centrality dependence

F_3: No centrality dependence
→ Fluctuations

Decorrelation in deformed nucleus: XeXe vs PbPb



ATLAS Collaboration, *Phys.Rev.Lett.* 126 (2021) 12, 122301

Pb+Pb Spherical

Central

Peripheral

Xe+Xe Deformed

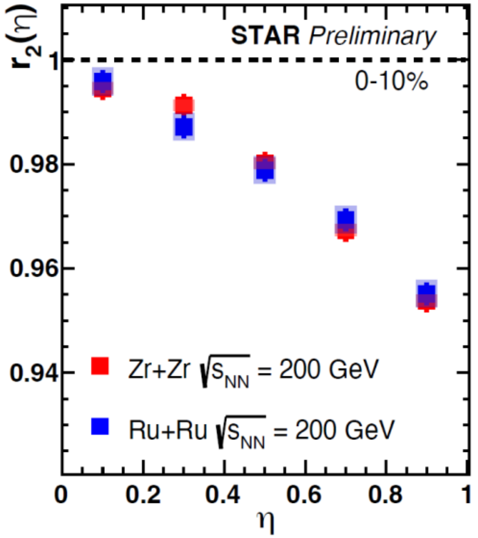
Central
Smaller F_2
→ More elliptic?

Peripheral
Larger F_2
Less elliptic?

Decorrelation in deformed nucleus: ZrZr vs RuRu

Longitudinal De-correlation of Anisotropic Flow at RHIC-STAR (Experiment)

G. Yan @Parallel A Mon. 15:00

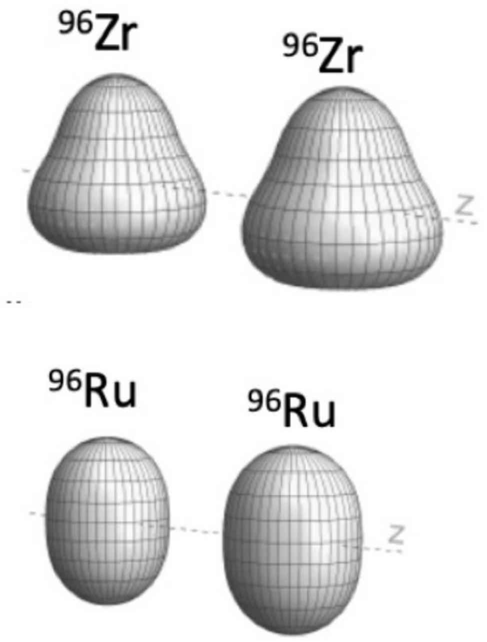


No obvious difference between Zr+Zr and Ru+Ru collisions

Ultra central collision yet to explore

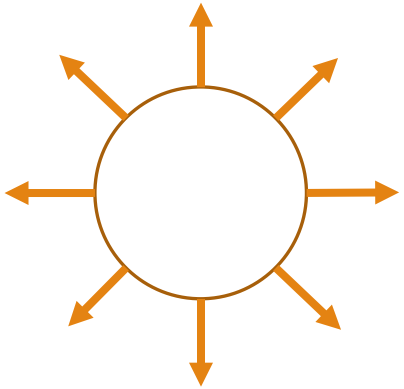
Longitudinal flow decorrelation in isobar collisions (Theory)

M. Nie @Poster E01

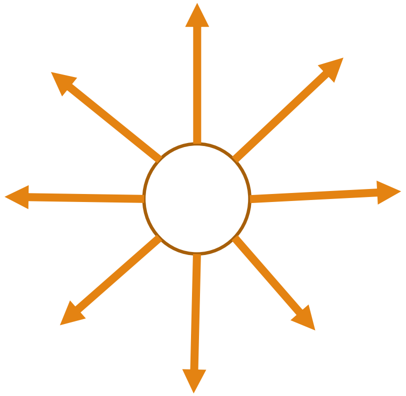


Chunjian Zhang and Jiangyong Jia Phys. Rev. Lett. 128 (2022) 2, 022301

Mean transverse momentum $\langle p_T \rangle$



r: Large → p_T: Small



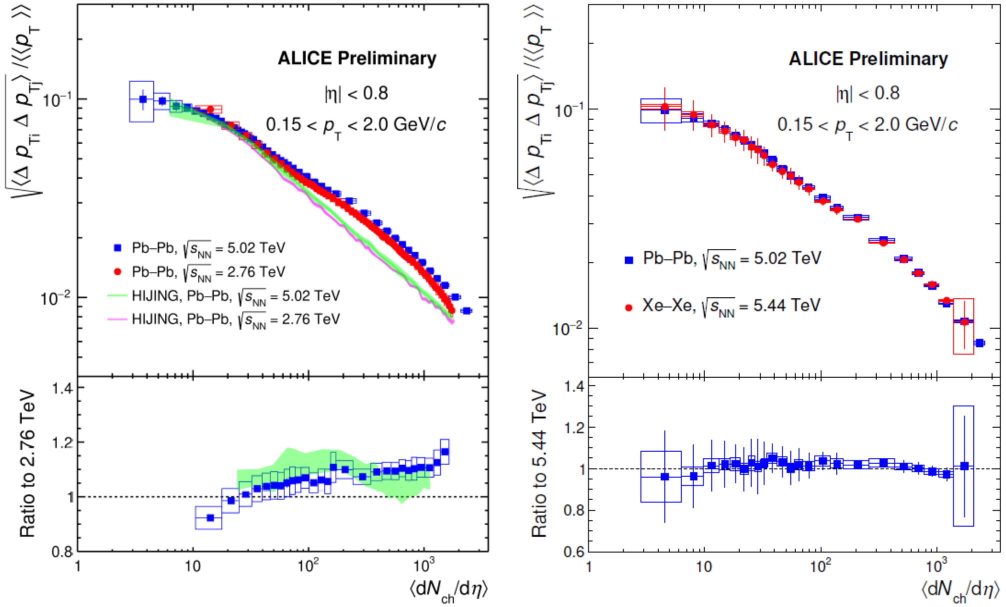
r: Small → p_T: Large

Initial size $\langle r \rangle \propto -\langle p_T \rangle$

Bozek, Broniowski, PRC 85, 044910, (2012)

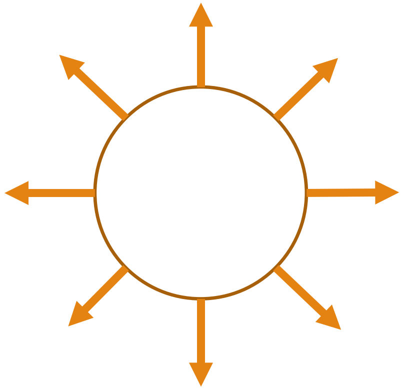
Mean transverse momentum in Pb-Pb and Xe-Xe collisions with ALICE

T. Tripathy @Parallel A Mon. 16:40



T. Tripathy (ALICE collaboration) arXiv:2211.14796v1 [nucl-ex]

$v_n - [p_T]$ Correlation (ρ_n)



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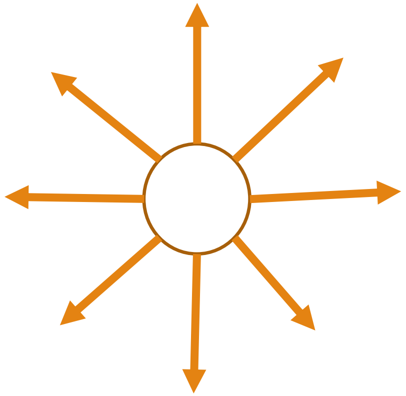


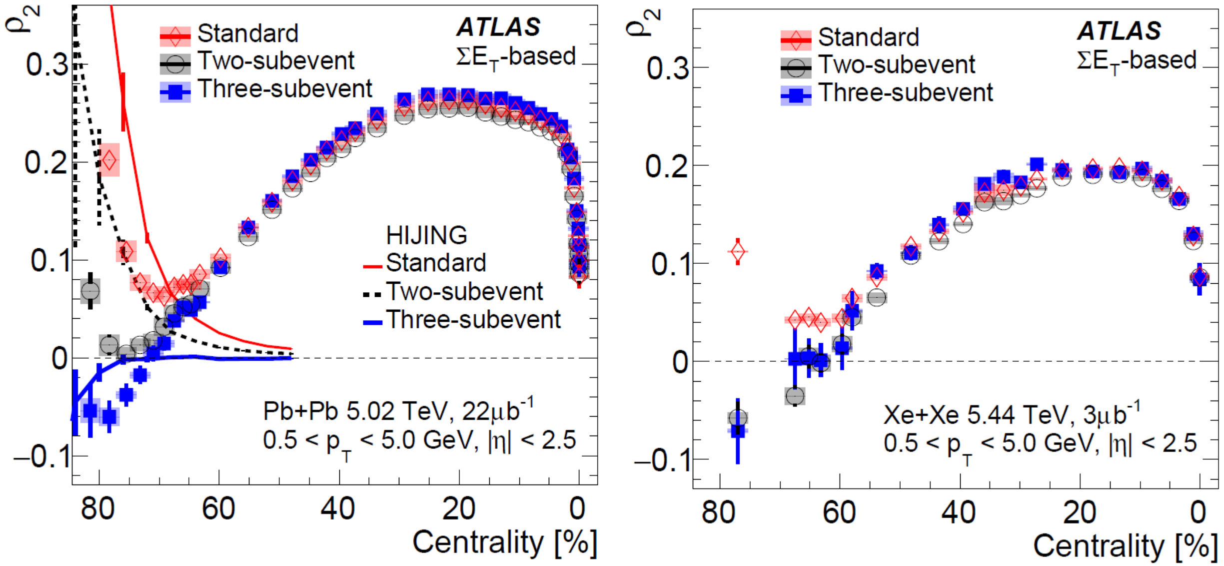
r: Small → p_T: Large

Initial size $\langle r \rangle \propto -\langle p_T \rangle$

Bozek, Broniowski, PRC 85, 044910, (2012)

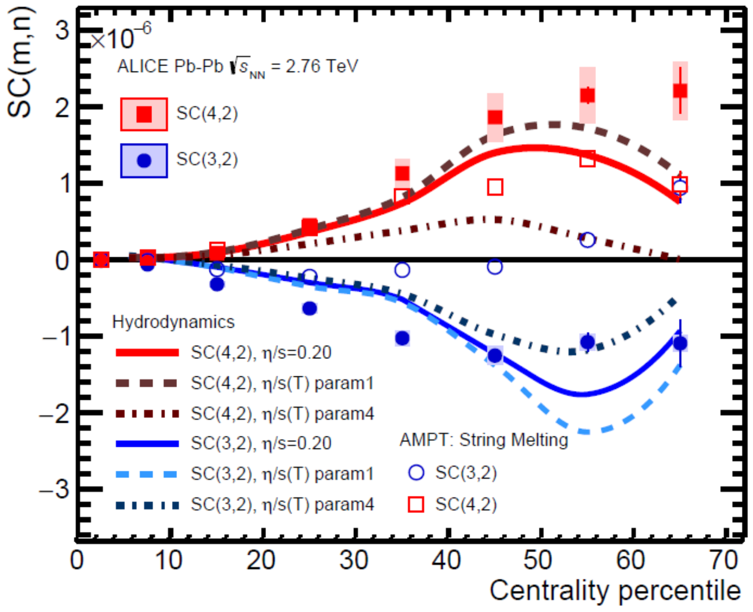
Pearson Correlation

$$\rho_n = \frac{cov(v_n^2, \delta p_T)}{\sqrt{var(v_n^2) var(\delta p_T)}}$$



ATLAS Collaboration, CERN-EP-2022-052
arXiv: 2205.00039

Symmetric Cumulants $SC(n,m)$



J. Adam *et al.*, (ALICE collaboration)
PRL 117, 182301 (2016)

Symmetric Cumulants:

$SC(n,m) = \langle v_n^2 v_m^2 \rangle - \langle v_n^2 \rangle \langle v_m^2 \rangle$

→ Evaluates correlation between v_n and v_m

$SC(4,2) > 0$

→ Correlation between v_2 and v_4

$SC(3,2) < 0$

→ Anti-correlation between v_2 and v_3

Mixed harmonic cumulants $nMHC$

Examples of mixed harmonic cumulants

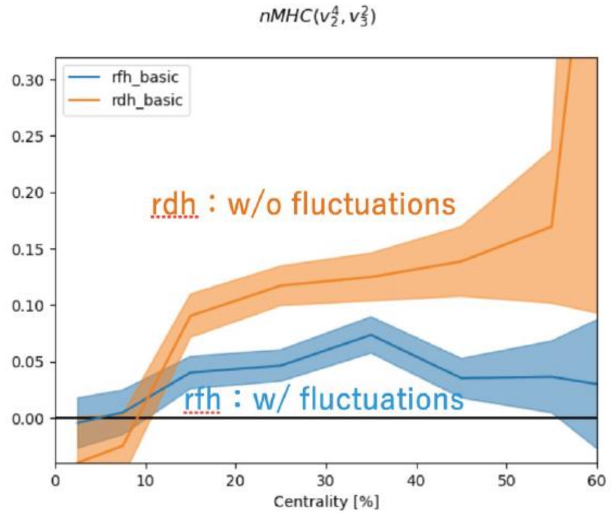
$MHC(v_2^4, v_3^2)$
$= \langle v_2^4 v_3^2 \rangle - 4\langle v_2^2 v_3^2 \rangle \langle v_2^2 \rangle - \langle v_2^4 \rangle \langle v_3^2 \rangle + 4\langle v_2^2 \rangle^2 \langle v_3^2 \rangle$

Normalized mixed harmonic cumulants

$nMHC$

Constraint on shear and bulk viscosities

Hydrodynamic Fluctuations

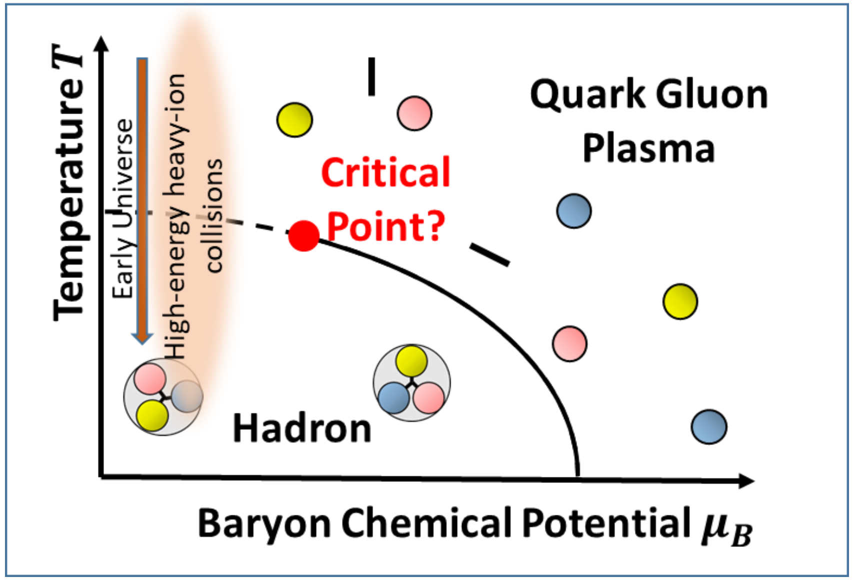


K. Oshima
@Poster F01

$nMHC(v_2^4, v_3^2)$ is sensitive to hydrodynamic fluctuations

$$\pi_{\mu\nu} = 2\eta\Delta^{\mu\nu}_{\alpha\beta}\partial^\alpha u^\beta + \xi^{\mu\nu}$$

Search for the phase transition



Schematic phase diagram of QCD

Net-proton fluctuations:

$$\langle(\delta N)^2\rangle = \sigma^2$$
$$\langle(\delta N)^3\rangle = S\sigma^3$$
$$\langle(\delta N)^4\rangle - 3\langle(\delta N)^2\rangle^2 = \kappa\sigma^4$$

σ: standard deviation
κ: Kurtosis
S: Skewness

Baryon number susceptibility:

$$C_k = \frac{1}{T}\frac{\partial^k P}{\partial(\mu_B/T)^k}$$

$$\frac{C_3}{C_2} = S\sigma, \frac{C_4}{C_2} = \kappa\sigma^2$$

Baryon number susceptibility diverge near QCD critical point
→ Study of net-proton fluctuations → Search for critical point!

Dynamical effects on the phase transition signal **L. Jiang @Parallel A Mon. 17:05**

Space-time evolution of critical fluctuations

$$\frac{d(\delta n)}{dt} = -\nabla \cdot \boldsymbol{\nu}$$

$$\tau_R \frac{d\boldsymbol{\nu}}{dt} + \boldsymbol{\nu} = \tilde{\lambda}\nabla \frac{\delta F}{\delta(\delta\sigma)} + \lambda\nabla \frac{\delta F}{\delta(\delta n)} + \boldsymbol{\xi}_n$$

$$\frac{d(\delta\sigma)}{dt} = -\Gamma \frac{\delta F}{\delta(\delta\sigma)} + \tilde{\lambda}\nabla^2 \frac{\delta F}{\delta(\delta n)} + \xi_\sigma$$

Fluctuation-dissipation relation

$$\langle \xi_i(x)\xi_j(x') \rangle = 2T\gamma_{ij}\delta^4(x - x')$$

$\Gamma, \tilde{\lambda}, \lambda$: Transport coefficient

T : Temperature

Critical fluctuations

Chiral condensate $\delta\sigma \equiv \bar{q}q - \langle \bar{q}q \rangle$

Baryon number density $\delta n \equiv \bar{q}\gamma_0 q - \langle \bar{q}\gamma_0 q \rangle$

Potential of free energy functional $F[\delta\sigma, \delta n]$

$$V(\delta\sigma, \delta n) = \frac{A}{2}\delta\sigma^2 + B\delta\sigma\delta n + \frac{C}{2}\delta n^2$$

Coupling term

Diffusion eq. of δn violates causality

Finite propagation speed

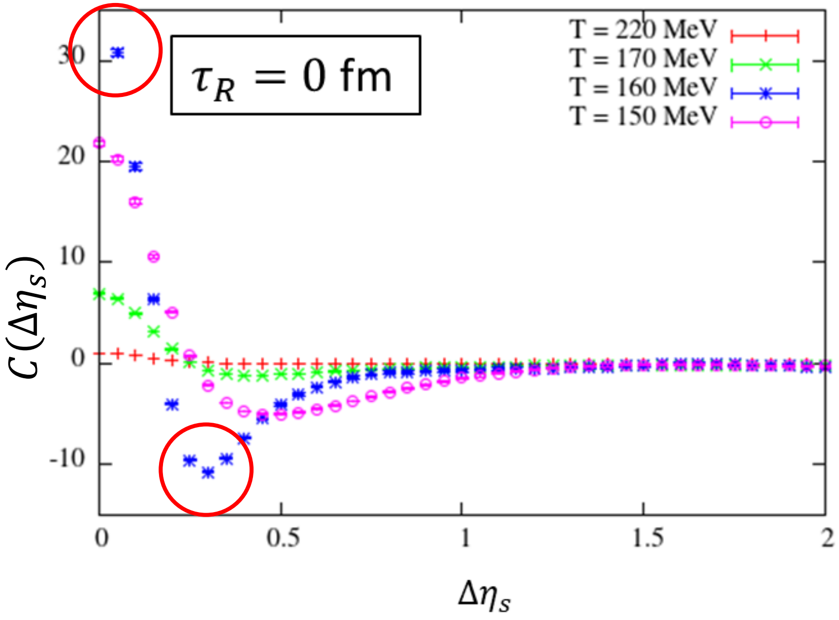
by introducing relaxation time τ_R

D.T. Son, M.A. Stephanov, Phys.Rev. D70 (2004) 056001
H. Fujii, M. Ohtani, Phys.Rev.D70:014016,2004

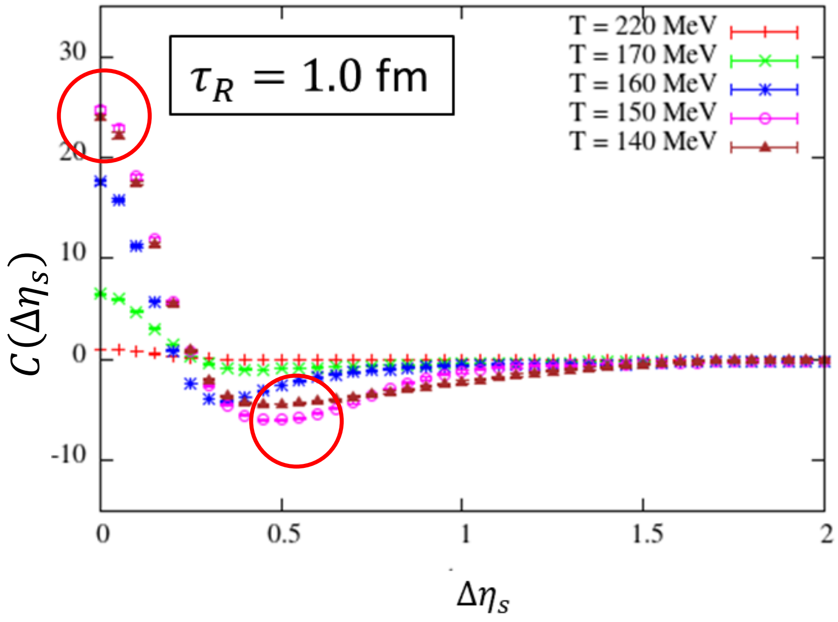
Space-time evolution of critical fluctuations

Correlation function:

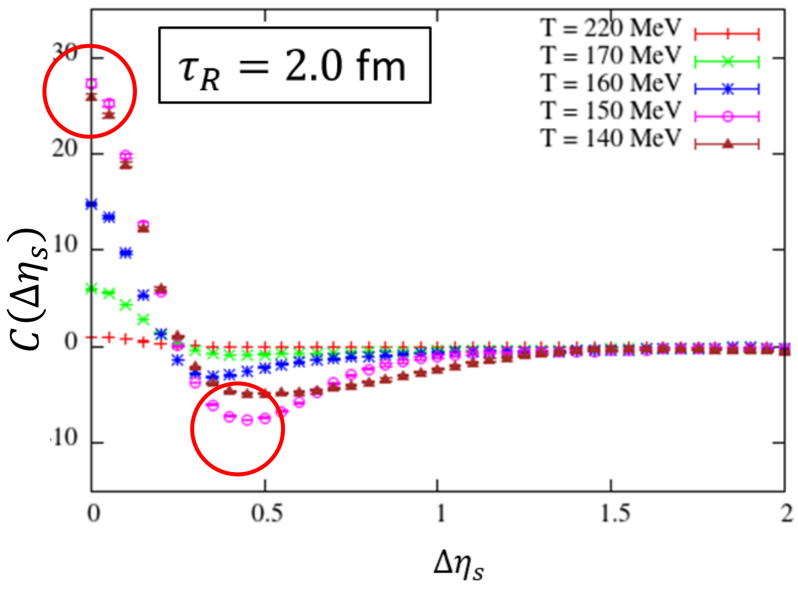
$$C(\Delta\eta_s) = \frac{\langle \delta\tilde{n}(\eta_s)\delta\tilde{n}(\eta_s + \Delta\eta_s)\rangle}{\langle \delta\tilde{n}(\eta_s)\delta\tilde{n}(\eta_s + \Delta\eta_s)\rangle_{T=220\ \mathrm{MeV}, \Delta\eta_s = 0}}$$



Peak at $T_c = 160$ MeV



Peak between 150 MeV and 160 MeV



Peak around $T \sim 150$ MeV

Finite relaxation time τ_R causes a time lag of response

Summary

- Collective flow v_n
- Decorrelation of flow r_n
- $v_n - [p_T]$ Correlation (ρ_n)
- Harmonic cumulants
- Critical fluctuations

- Hydrodynamic models
- Constraints on 3D initial condition
- Collision geometry
- Constraint on shear and bulk viscosities
- Search for QCD critical point

Fluctuations and correlations

Key for understanding heavy ion collision dynamics!