Probing the initial state and evolution of isobaric systems in relativistic nuclear collisions
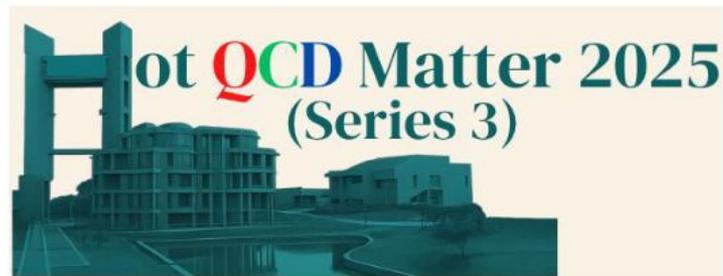
Amit Paul

(PhD Scholar)

In collaboration with: Dr. Rupa Chatterjee

Variable Energy Cyclotron Centre, Kolkata, India
Homi Bhabha National Institute, Mumbai, India

ot QCD Matter 2025
(Series 3)

05/09/2025

Outlines

- Introduction

- Initial Profile

- Spectra and Anisotropic flow

- Summary and Conclusions

Introduction

Isobaric collisions involve collisions between nuclei with same mass numbers but different proton numbers.

RHIC Isobar Collisions at $\sqrt{s_{NN}} = 200$ GeV $\begin{cases} {}^{96}_{44}\text{Ru} + {}^{96}_{44}\text{Ru} \\[1em] {}^{96}_{40}\text{Zr} + {}^{96}_{40}\text{Zr} \end{cases}$

[STAR Collaboration], Phys. Rev. C **105**, 014901 (2022)

Ruthenium (Ru) $\longrightarrow$ Quadrupole deformation

Zirconium (Zr) $\longrightarrow$ Octupole deformation

The difference in deformation parameters between the isobaric nuclei set Ru+Ru and Zr+Zr leads to distinct initial state geometries.

These geometric differences influence the initial spatial eccentricities, which in turn affect the **anisotropic flow** parameters.

Initial Profile

Woods–Saxon nuclear density profile:

$$\rho(r, \theta) = \frac{\rho_0}{1 + \exp\left[\frac{r - R(\theta)}{\xi}\right]}$$

Nucleus	A	R_A (fm)	ξ (fm)	β_2	β_3
Ruthenium (Ru)	96	5.09	0.46	0.162	0
Zirconium (Zr)	96	5.02	0.52	0.06	0.20

[C. Zhang, S. Bhatta and J. Jia, Phys. Rev. C **106**, 031901 (2022)]

$$R(\theta) = R_A \left[1 + \beta_2 Y_{20}(\theta) + \beta_3 Y_{30}(\theta)\right]$$

Initial condition: Initial energy density distribution in the transverse plane:

$$\varepsilon(x, y; b) = K \left[(1 - \alpha) \, n_{\mathrm{WN}}(x, y; b) + \alpha \, n_{\mathrm{BC}}(x, y; b)\right]$$

$K = \varepsilon_0 / [(1 - \alpha) \, n_{\mathrm{WN}}(0, 0; 0) + \alpha \, n_{\mathrm{BC}}(0, 0; 0)]$
Fraction of the contribution from binary collisions, $\alpha = 0.05$
Initial proper time, $\tau_0 = 0.4$ fm/c
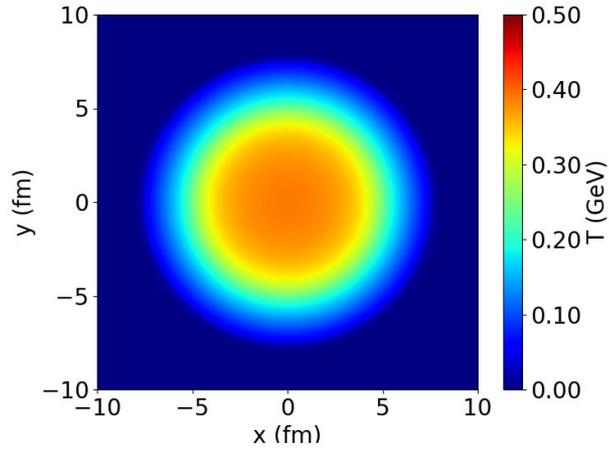Freeze-out temperature, $T_{\mathrm{FO}} = 137$ MeV

System	Orientations	ε_0 (GeV/fm^3)
Ru+Ru	tip-tip	43.28
	body-body	34.79
Zr+Zr	tip-tip	38.02
	body-body	37.21

$$\frac{dN_{\mathrm{ch}}}{dy} = \frac{\langle N_{\mathrm{part}} \rangle}{2} \left[0.78 \ln\left(\sqrt{s}\right) - 0.4\right] \quad \text{[B. Alver \textit{et al.}, (PHOBOS) Phys. Rev. C \textbf{83}, 024913 (2011)]}$$
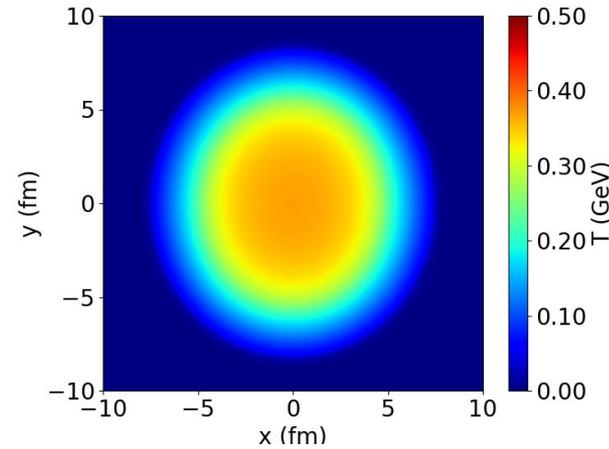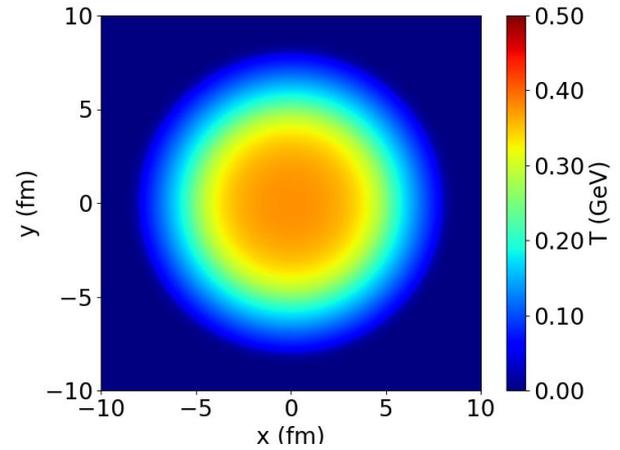
$$\frac{dN_{\mathrm{ch}}}{dy} \propto A_{\mathrm{T}} \, s \, \tau, \quad s \propto \varepsilon^{3/4}$$

Hydro framework: Boost invariant ideal hydrodynamic framework of relativistic heavy-ion collisions is performed using MUSIC. [B. Schenke, S. Jeon, and C. Gale, Phys. Rev. C **82**, 014903 (2010)]
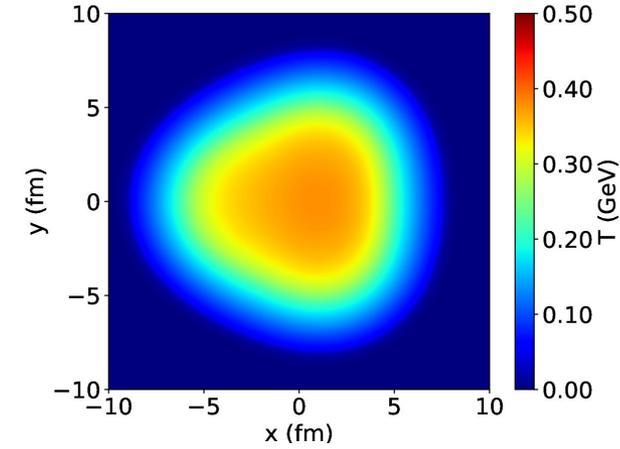
Temperature distribution at the initial time
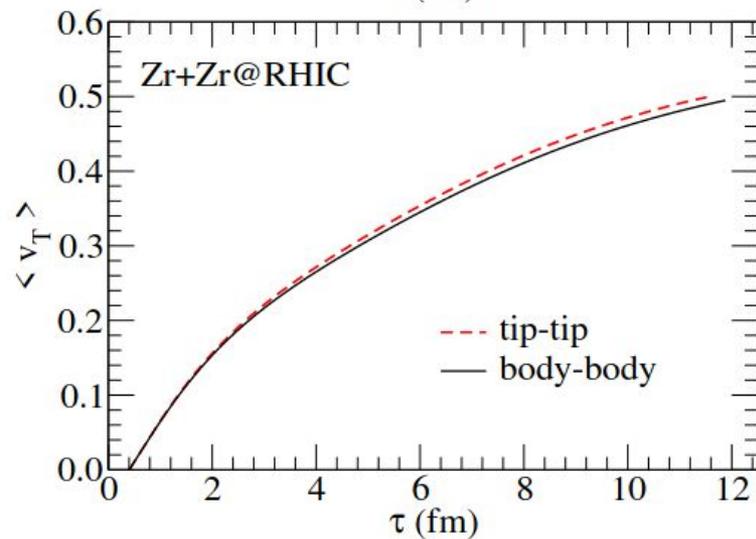

tip-tip orientation

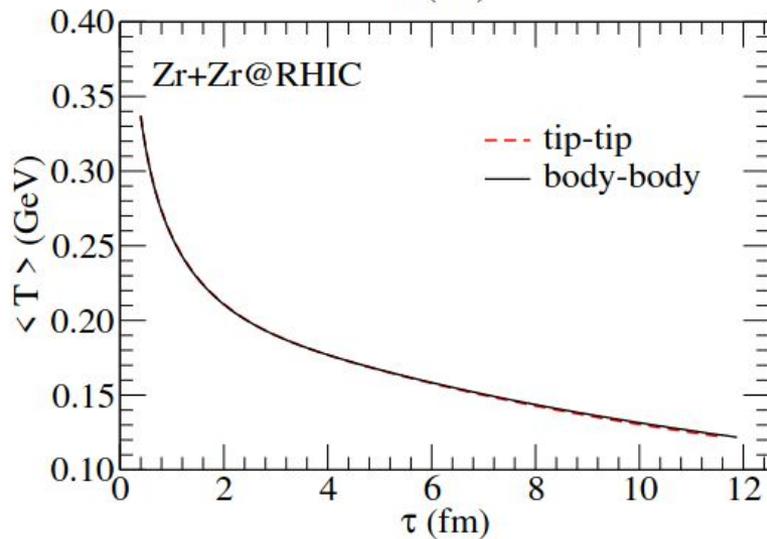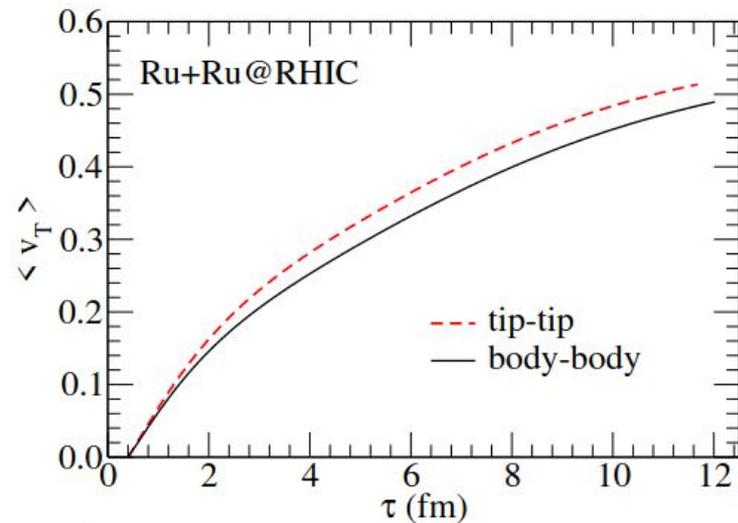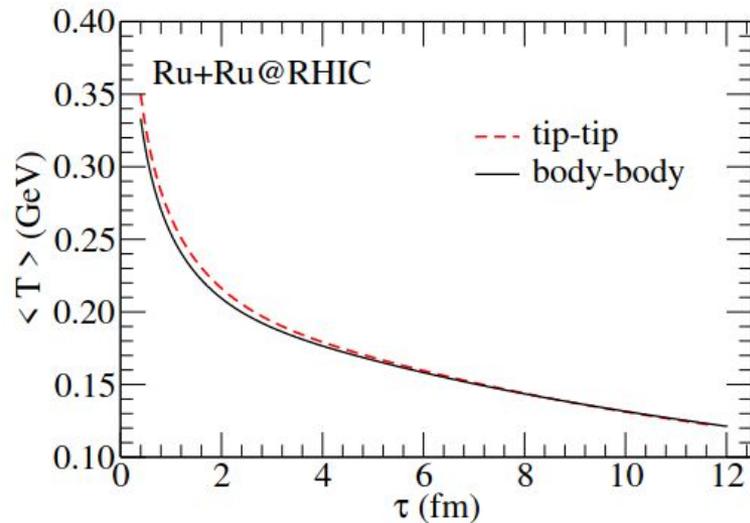body-body orientation

Ru+Ru

Zr+Zr

Spatial Eccentricity

$$\epsilon_n = \frac{\sqrt{\langle r^2 \cos(n\phi)\rangle^2 + \langle r^2 \sin(n\phi)\rangle^2}}{\langle r^2 \rangle}$$
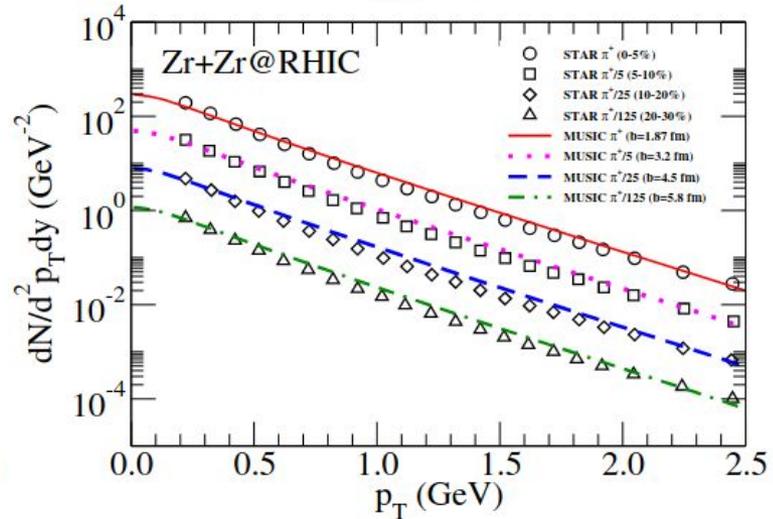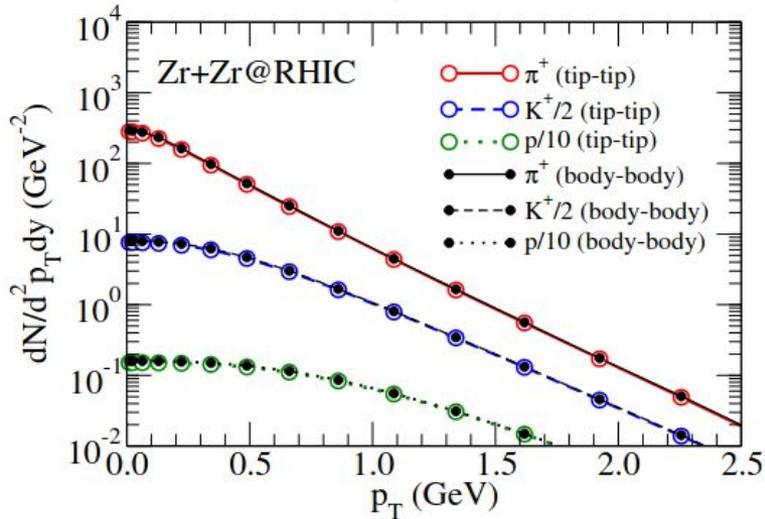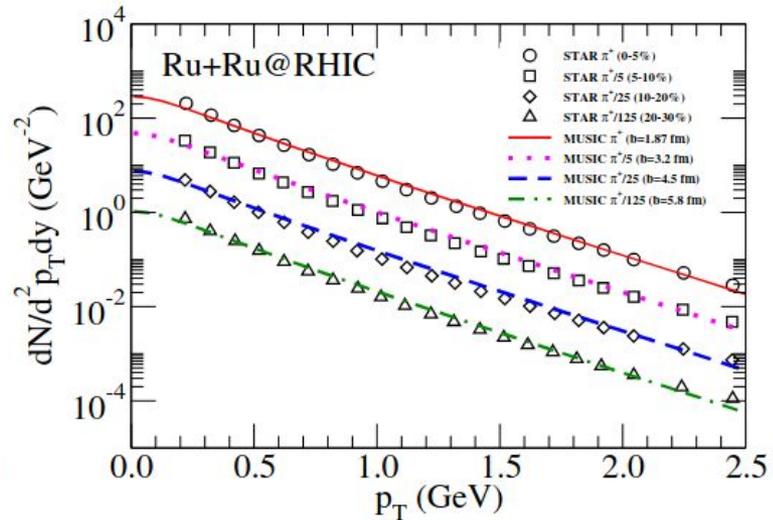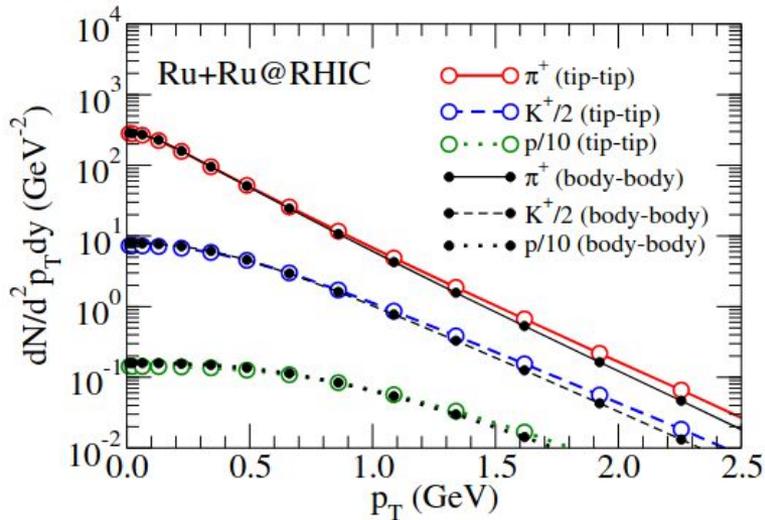
[B. Alver and G. Roland, Phys. Rev. C 81, 054905 (2010)]

AA	$\epsilon_2(\tau_0)$	$\epsilon_3(\tau_0)$	$\langle T(\tau_0)\rangle$ (MeV)
Ru+Ru tip-tip	0	0	350
Ru+Ru body-body	0.146	0	333
Zr+Zr tip-tip	0	0	337
Zr+Zr body-body	0.062	0.158	336

Time evolution of hydrodynamic parameters

The average at a time step is obtained as:

$$\langle f(\tau) \rangle = \frac{\int \int dx\, dy\, \varepsilon(x, y, \tau)\, f(x, y, \tau)}{\int \int dx\, dy\, \varepsilon(x, y, \tau)}$$
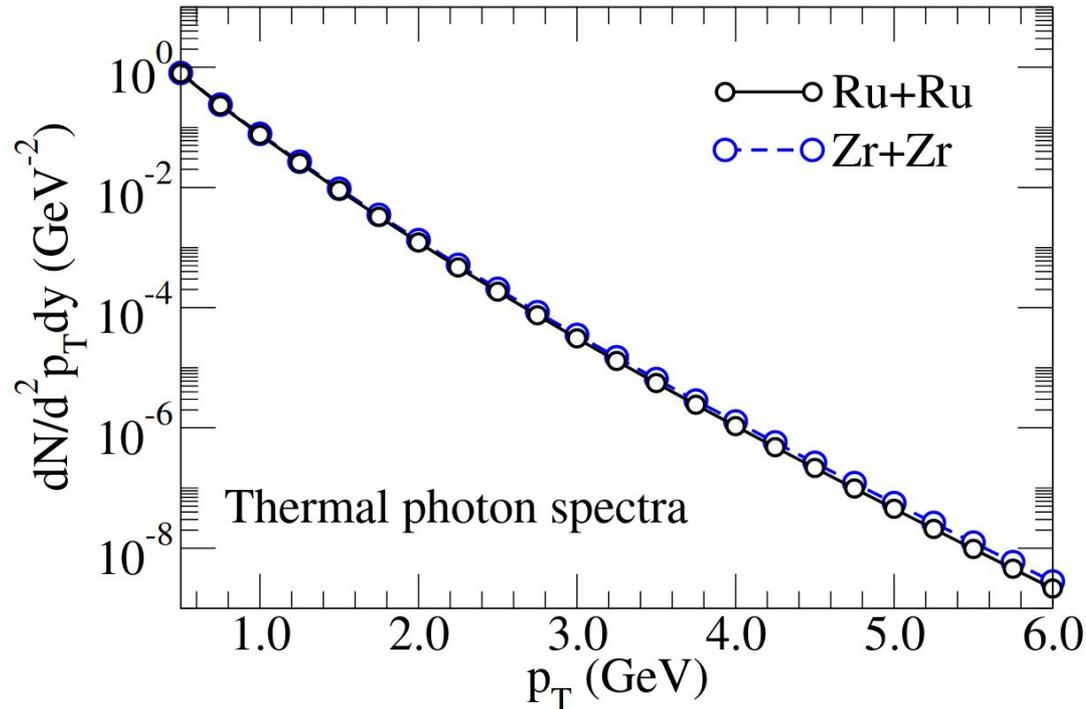
Particle spectra

p_T spectra are not sensitive to the orientations of the collisions.

Photons from relativistic heavy ion collisions

Photons are emitted throughout the lifetime of the system and are largely unaffected by final state interactions.

Thermal photon spectra of for **body-body** orientations of Ru+Ru and Zr+Zr collisions.

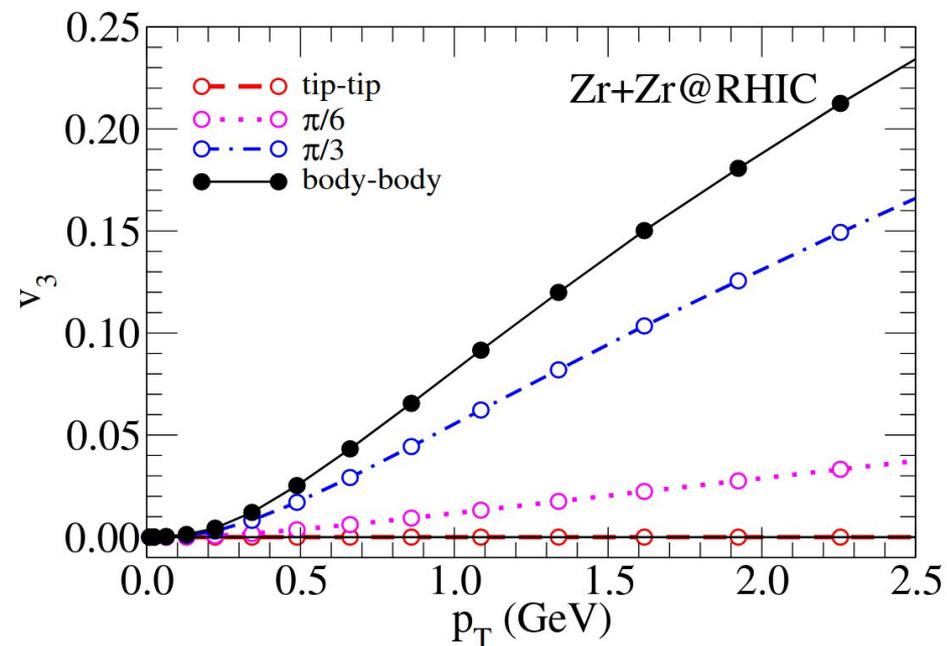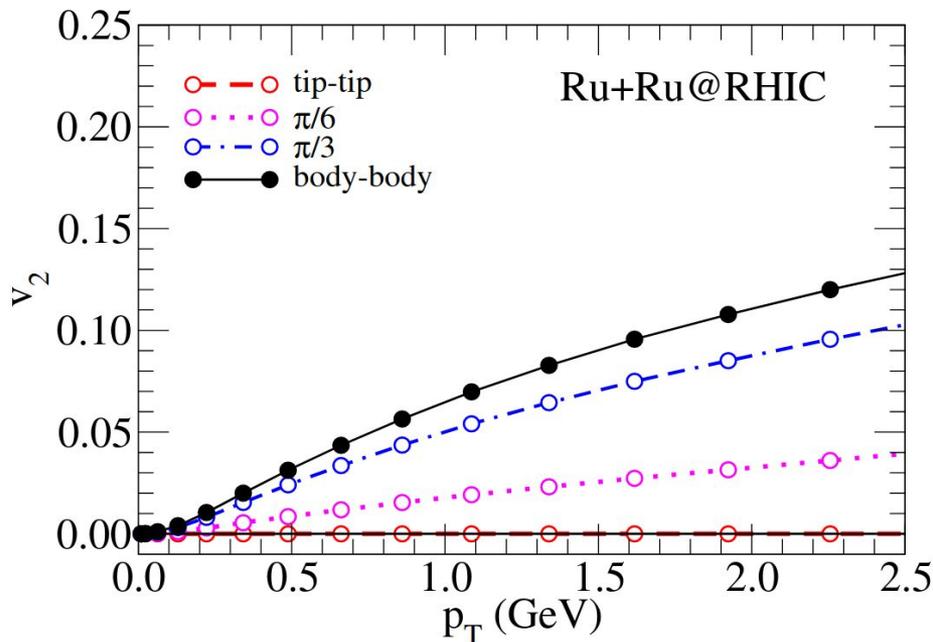Photon production in QGP ⟹ P. B. Arnold, G. D. Moore and L. G. Yaffe, JHEP **12**, 009 (2001)

Photon production from Hadrons ⟹ S. Turbide, R. Rapp and C. Gale, Phys. Rev. C **69**, 014903 (2004)

Anisotropic flow

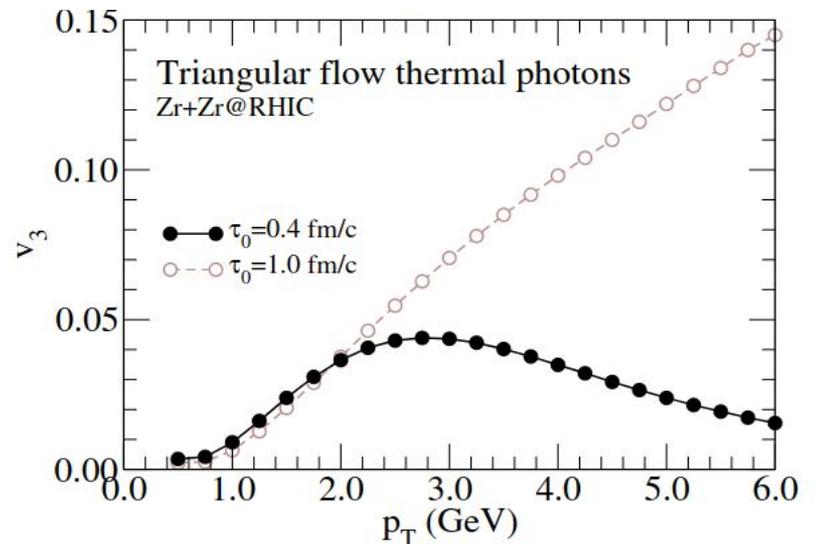Anisotropic flow is one of the prominent signatures of the **collective behaviour** of the system produced in relativistic heavy ion collisions.
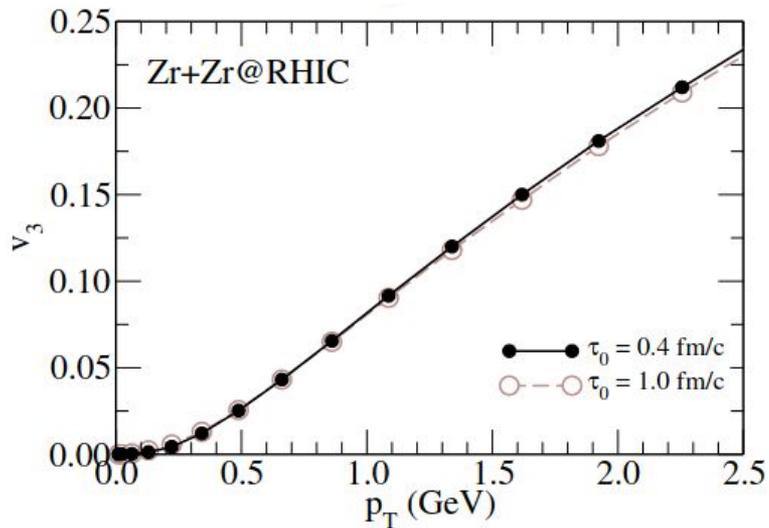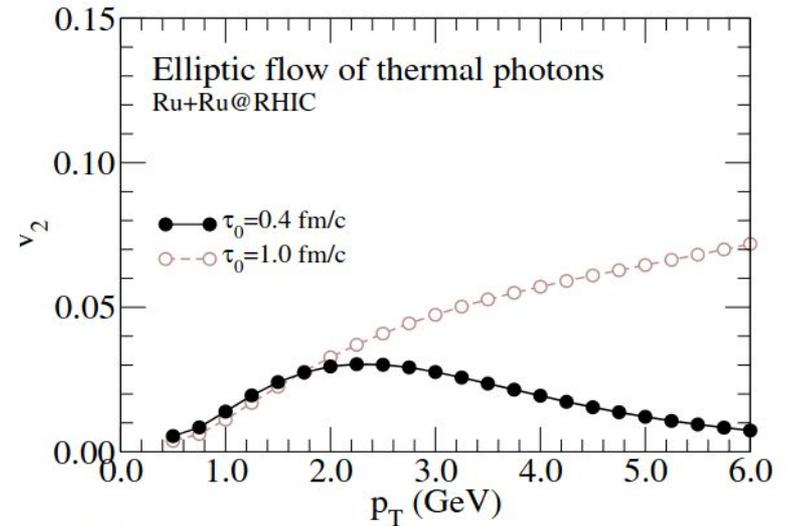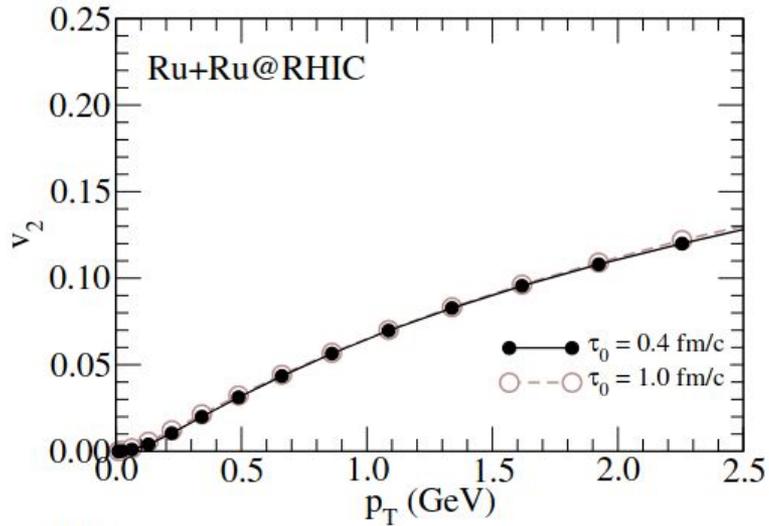
The anisotropic flow parameters are quantified by decomposing the particle distribution in Fourier expansion as :

$$E\frac{dN}{d^3p} = \frac{dN}{p_T \, dp_T \, dy \, d\phi} = \frac{dN}{p_T \, dp_T \, dy} \cdot \frac{1}{2\pi}\left[1 + \sum_{n=1}^{\infty} 2v_n \cos(n\phi)\right]$$

Pions

Anisotropic flow

Pions

Thermal photons

Summary and Conclusions

- The initial state and subsequent evolution for the different orientations of the most central Ru+Ru and Zr+Zr collisions at 200A GeV at RHIC has been investigated using appropriate initial conditions and the MUSIC hydrodynamical model.

- Charged particle spectra and thermal photon spectra are found to be unaffected by the initial eccentricity of the collision zone.

- Significant anisotropic flow of charged particle and photons for isobaric system are observed, highlighting the role of nuclear deformation in shaping final state observables.

- Photon anisotropic flow is found to be considerably more sensitive to the initial state than charged particle anisotropic flow, indicating that photon measurements in isobaric collisions have strong potential to constrain initial state modeling.

THANK YOU

Glauber model

Nuclear density distribution:
$$\rho(r, \theta) = \frac{\rho_0}{1 + \exp\left[\frac{r - R(\theta)}{\xi}\right]} \qquad \int \rho\, d^3 r = A$$

Nuclear thickness function:
$$T_A(x, y) = \int dz\, \rho_A(x, y, z)$$

Binary nucleon-nucleon collisions:
$$n_{\mathrm{BC}}(x, y; b) = \sigma_{\mathrm{NN}} T_A\left(x + \tfrac{b}{2}, y\right) T_B\left(x - \tfrac{b}{2}, y\right)$$

Wounded nucleons (participating nucleons):
$$n_{\mathrm{WN}}(x, y; b) = T_A\left(x + \tfrac{b}{2}, y\right) \left[1 - \left(1 - \frac{\sigma_{\mathrm{NN}} T_B\left(x - \tfrac{b}{2}, y\right)}{B}\right)^B\right]$$
$$+ T_B\left(x - \tfrac{b}{2}, y\right) \left[1 - \left(1 - \frac{\sigma_{\mathrm{NN}} T_A\left(x + \tfrac{b}{2}, y\right)}{A}\right)^A\right]$$

$\sigma_{\mathrm{NN}} = 4.2\,\mathrm{fm}^2$ at $\sqrt{s_{NN}} = 200$ GeV

200A GeV Au+Au@RHIC

Parameters:

WS parameters-

$R_A = 6.38$ fm
$\xi = 0.535$ fm

Hydro parameters-

$\alpha = 0.05$
$\varepsilon_0 = 55$ GeV/fm^3
$\tau_0 = 0.4$ fm
$T_{\text{FO}} = 137$ MeV

p_T spectra of Au+Au collision from MUSIC compared to 0-5% centrality PHENIX data. The used impact parameter was b = 2.4 fr

Equation of State: Lattice based equation of state.
[P. Huovinen and P. Petreczky, Nucl. Phys. A837 26 (2010)]

MUSIC: **[MUS**cl for **I**on **C**ollisions**]** — Hydrodynamic code for heavy-ion collisions.

NB: MUSCL — Monotonic Upstream-centered Scheme for Conservation Laws (numerical method used to solve partial differential equations)

Photon production rate

$$R = \frac{E\,dN}{d^3p\,d^4x} \qquad\qquad E\frac{dN}{d^3p} = \int d^4x\; R\left(E^*(x), T(x)\right)$$

$$\frac{dN}{d^2p_T dy} = \int_{\tau_0}^{\tau_{\max}} \tau\,d\tau \int_{x_{\min}}^{x_{\max}} dx \int_{y_{\min}}^{y_{\max}} dy \int_{\eta_{\min}}^{\eta_{\max}} d\eta\; R(E^*, T)$$
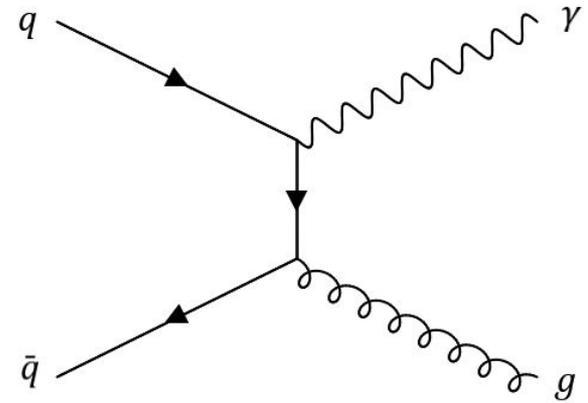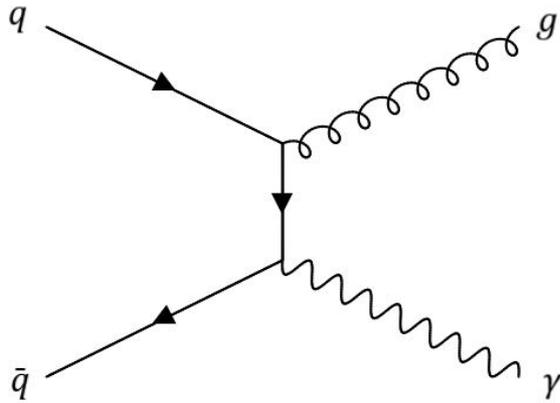
$$E^* = u^\mu p_\mu$$
$$= \gamma\left(p_T \cosh(y-\eta) - p_x v_x - p_y v_y\right)$$
$$= \gamma\left[p_T \cosh(y-\eta) - p_T \cos\phi \cdot v_x - p_T \sin\phi \cdot v_y\right]$$

$$u^\mu = \gamma(\cosh\eta, v_x, v_y, \sinh\eta)$$

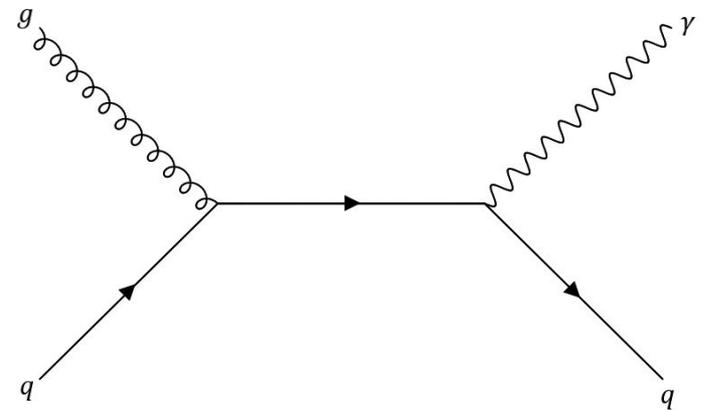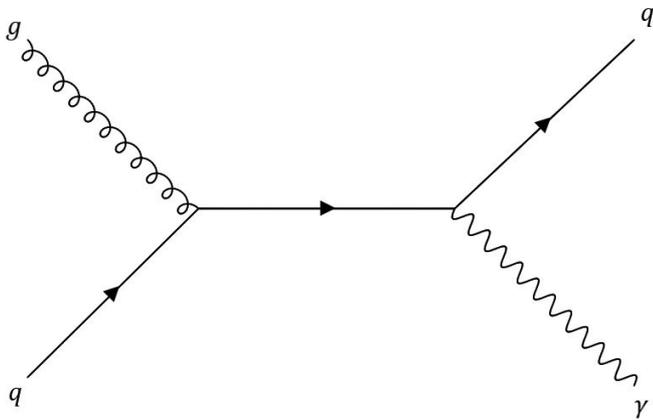$$\gamma = \frac{1}{\sqrt{1 - v_x^2 - v_y^2}}$$

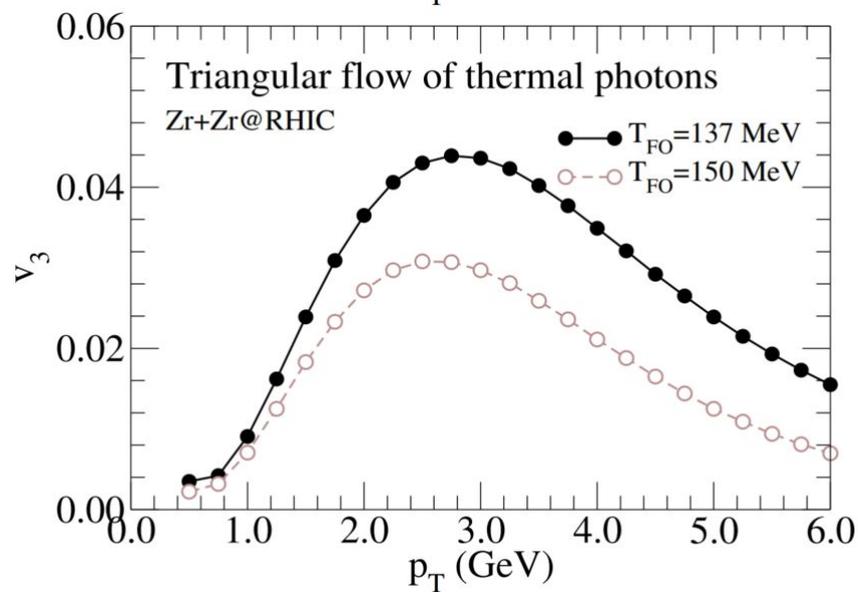$$R = q_f \times \mathrm{Rate}_{\mathrm{QGP}} + (1 - q_f) \times \mathrm{Rate}_{\mathrm{Hadron}} \qquad q_f = \begin{cases} 0, & T \leq T_c \\ 1, & T > T_c \end{cases}$$
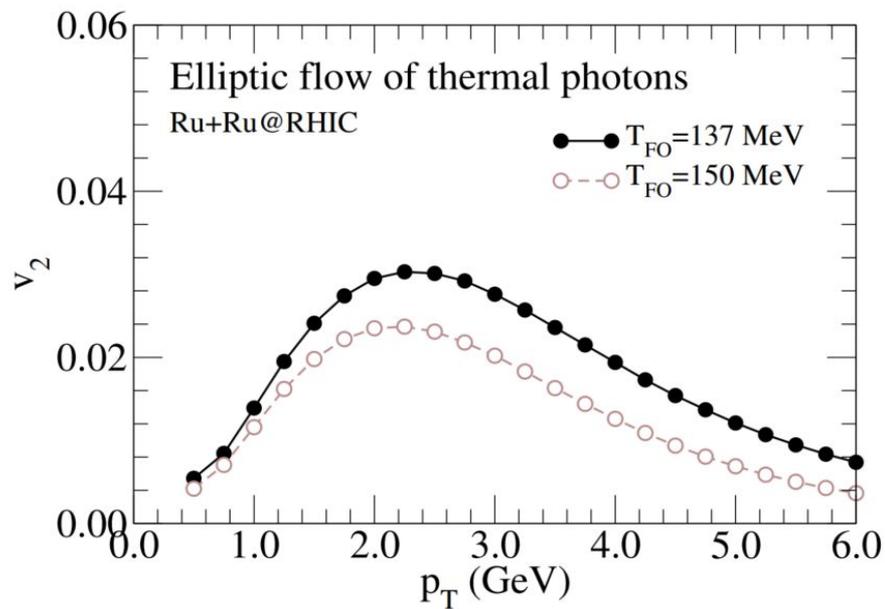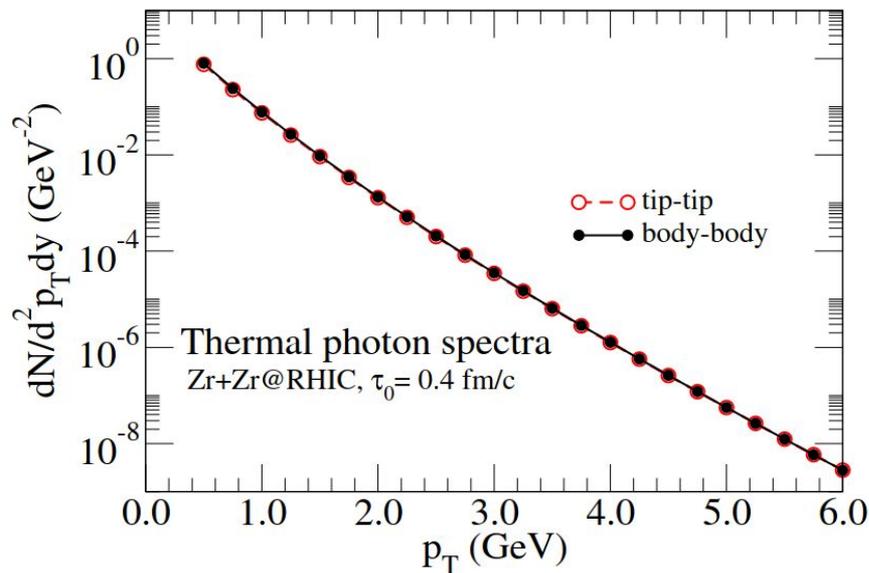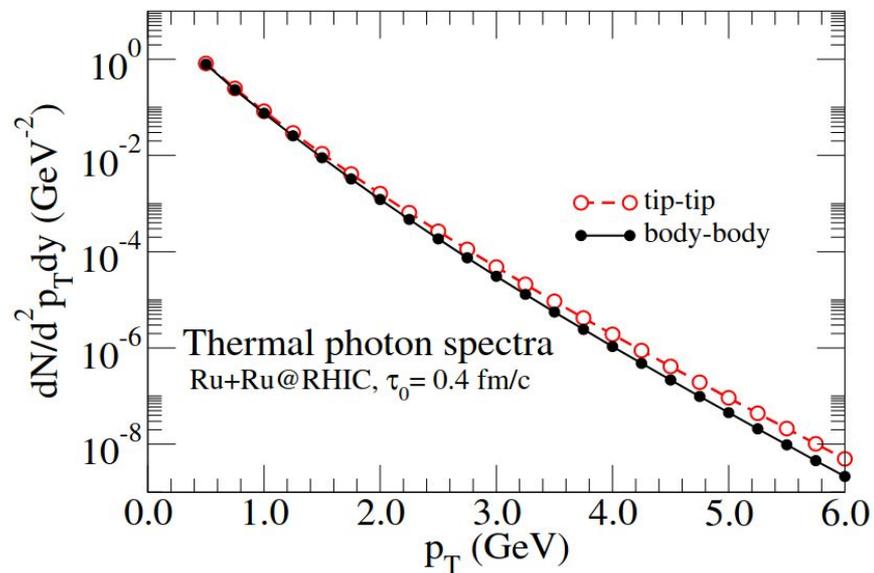
Photon production in QGP

Annihilation process: $q + \bar{q} \rightarrow g + \gamma$

Compton process: $q + g \rightarrow q + \gamma$

Thermal photon spectra
Ru+Ru@RHIC, τ_0= 0.4 fm/c

- ○ – ○ tip-tip
- ● – ● body-body

dN/d^2p_Tdy (GeV^{-2})

p_T (GeV)

Thermal photon spectra
Zr+Zr@RHIC, τ_0= 0.4 fm/c

- ○ – ○ tip-tip
- ● – ● body-body

dN/d^2p_Tdy (GeV^{-2})

p_T (GeV)

Elliptic flow of thermal photons
Ru+Ru@RHIC

- ● – ● T_{FO}=137 MeV
- ○ – ○ T_{FO}=150 MeV

v_2

p_T (GeV)

Triangular flow of thermal photons
Zr+Zr@RHIC

- ● – ● T_{FO}=137 MeV
- ○ – ○ T_{FO}=150 MeV

v_3

p_T (GeV)

Length [fm] 1 fm= 10^{-15} m

Time [fm/c] 1 fm/c = 3.3×10^{-24} s

Temperature [MeV] 1 MeV= 11.6×10^9 K

1 fm^{-1} = 0.19732 GeV