Energy and Baryon Emission Surfaces in Relativistic Heavy-Ion Collisions via HBT Correlations

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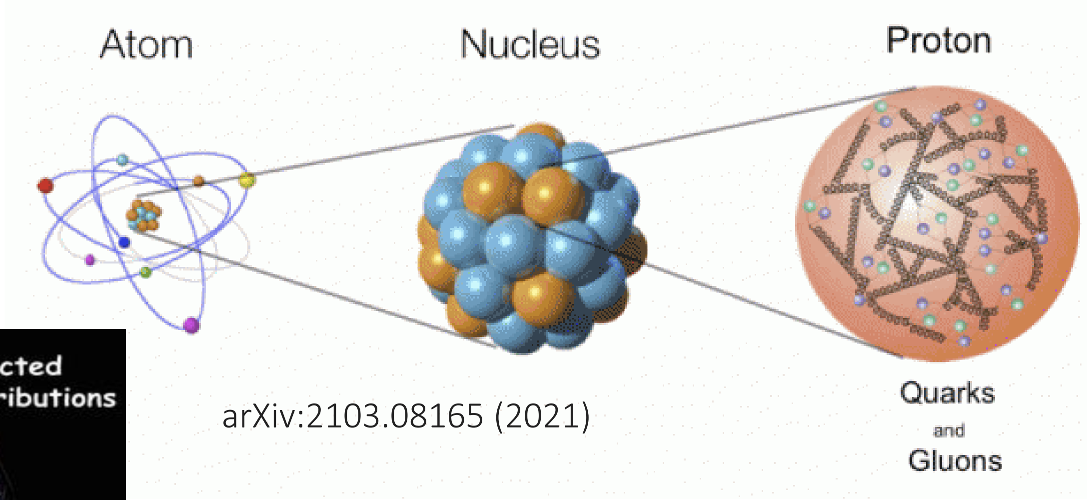
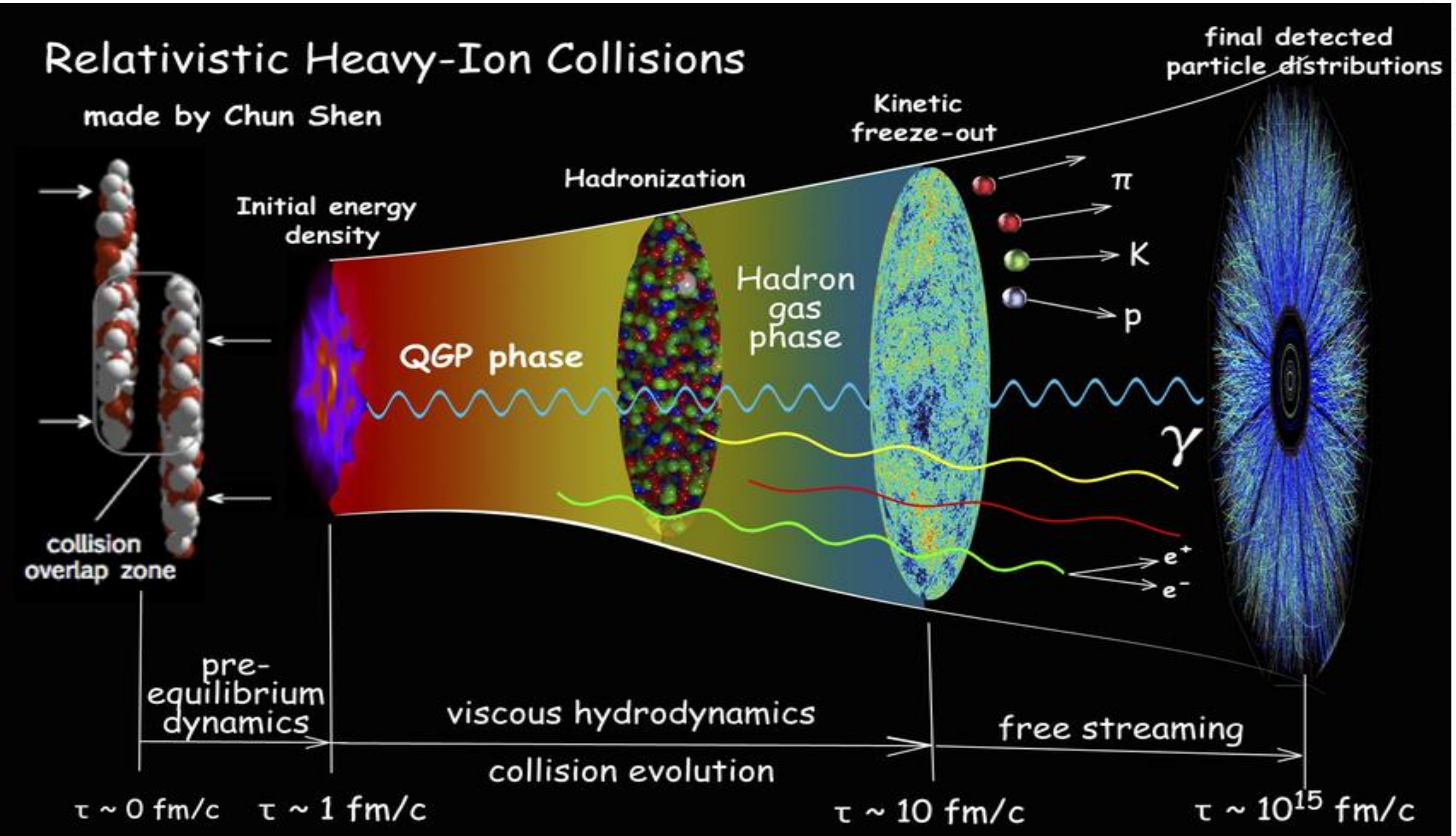
Introduction

- Under normal conditions, quarks and gluons are confined in hadrons.
- Under extreme conditions, quarks and gluons are deconfined to form QGP.



arXiv:2103.08165 (2021)



Quark-Gluon Plasma (QGP) created microseconds after the Big Bang, can be recreated in high energy heavy-ion collisions experiments like LHC (CERN, Switzerland) & RHIC (BNL, USA).

Hybrid Model

Consists of four components:

1. **GICG** (Glauber Initial Condition Generator) - Models the initial energy density distribution using geometry of nuclei.

2. **MUSIC** (Modular Unified Solver for the Initial Condition of heavy- ion collisions) - Simulates QGP evolution with relativistic hydrodynamics.

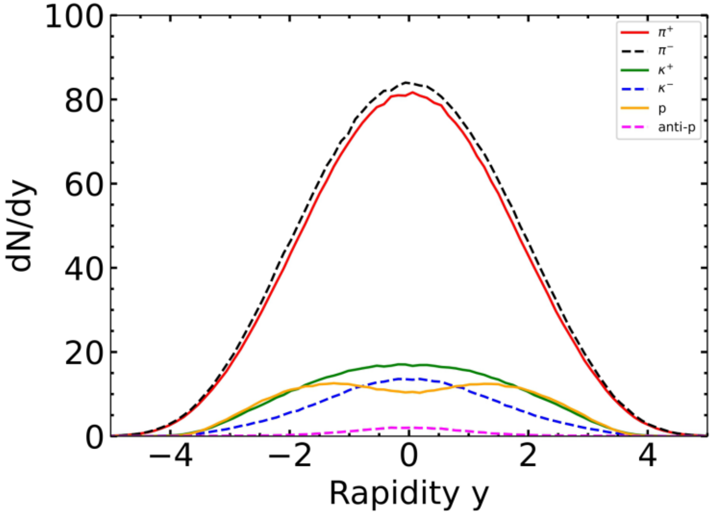
3. **ISS** (Isochronous Spectra Sampler) - Samples particles from the freeze-out hypersurface using the Cooper-Frye formula.

4. **URQMD** (Ultra-Relativistic Quantum Molecular Dynamics) - Tracks hadronic interactions in the final phase.

Common Bulk Observables

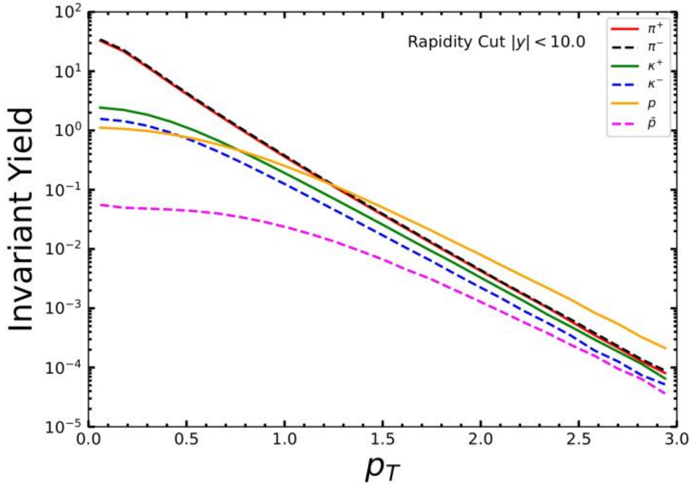
Rapidity:

$$y = \frac{1}{2} ln \left(\frac{E + p_Z}{E - p_Z} \right)$$



Invariant Yield:

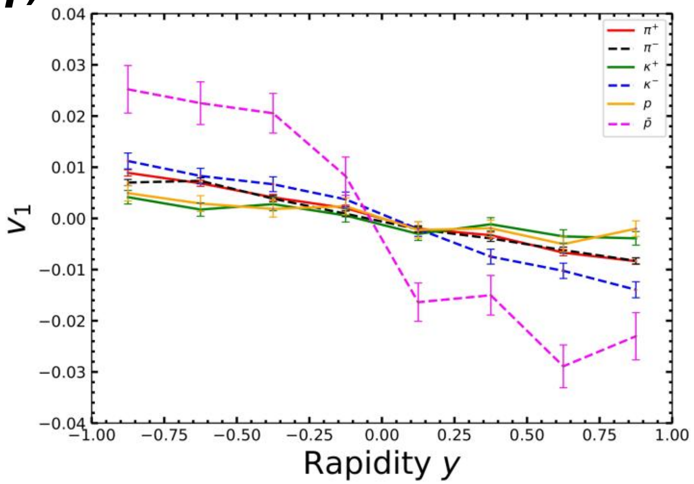
$$E \frac{d^2 N}{2\pi p_T dp_T dy}$$



Anisotropic Flow Coefficients (v_n)

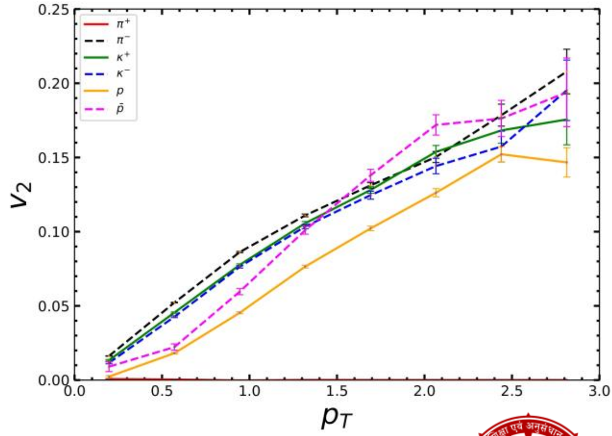
Directed Flow (v_1):

$$v_1 = \langle cos(\phi - \Psi_{RP_1}) \rangle$$



Elliptic Flow (v_2):

$$v_2 = \langle cos(2(\phi - \Psi_{RP_2})) \rangle$$



Studying HBT Radii via HBT Interferometry

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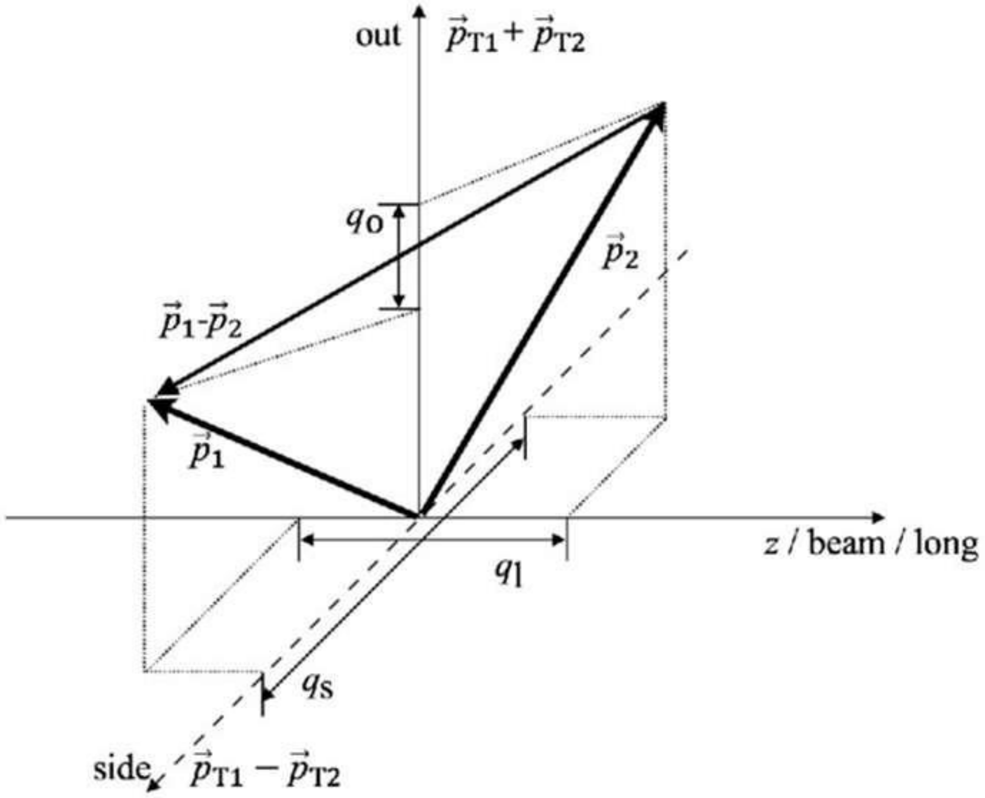
HBT Interferometry (or Femtoscopy)

- In high-energy heavy-ion collisions, HBT interferometry (or Femtoscopy) provides key insights into the geometry and dynamics of particle-emitting sources by measuring two-particle correlations.



The two-particle correlation function is defined as:

$$C(p_1, p_2) = \frac{W_2(p_1, p_2)}{W_1(p_1)W_1(p_2)}$$

where,

$$W_1(p) = E_p \frac{dN}{d^3p} = \int d^4x S(x,p)$$

$$W_2(p_1,p_2) = E_{p_1}E_{p_2}\frac{dN}{d^3p_1 d^3p_2} = \int d^4x_1 d^4x_2 S(x_1,x_2,p_1,p_2)$$

$$S(x,p) = \sum E_p \frac{dN}{d^3p d^4x}$$

- Longitudinally Co-Moving System (LCMS) frame of reference – Net $p_z = 0$.

- Bertsch-Pratt Parameterization: out-side-long axes.

Extracting the HBT Radii

- The three Hanbury Brown-Twiss radii are represented as : R_{out} , R_{side} & R_{long} along the three out-side-long axes.

- To extract the three HBT radii from the correlation function $C(q, k_T)$, where $q = (p_1 - p_2)$ & $k_T = ½ (p_1 + p_2)$, we assume that the single particle emission function $S(x, p)$ is a three-dimensional ellipsoid with a Gaussian density profile. Using this form of definition, we obtain the correlation function as:

$$C(q, k_T) = 1 + \lambda exp\left[-R^2_{out}(k_T)q^2_{out} - R^2_{side}(k_T)q^2_{side} - R^2_{long}(k_T)q^2_{long}\right]$$

Correlation Function Plots for Pions & Kaons

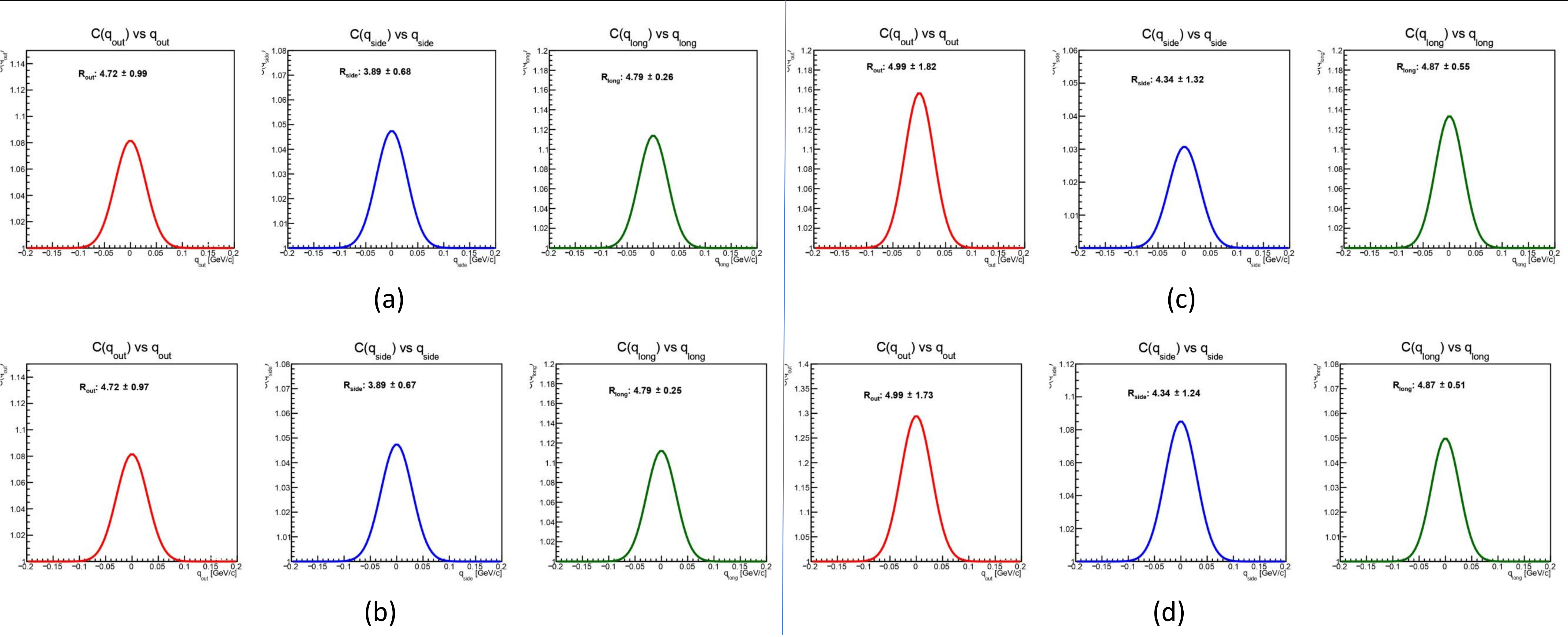
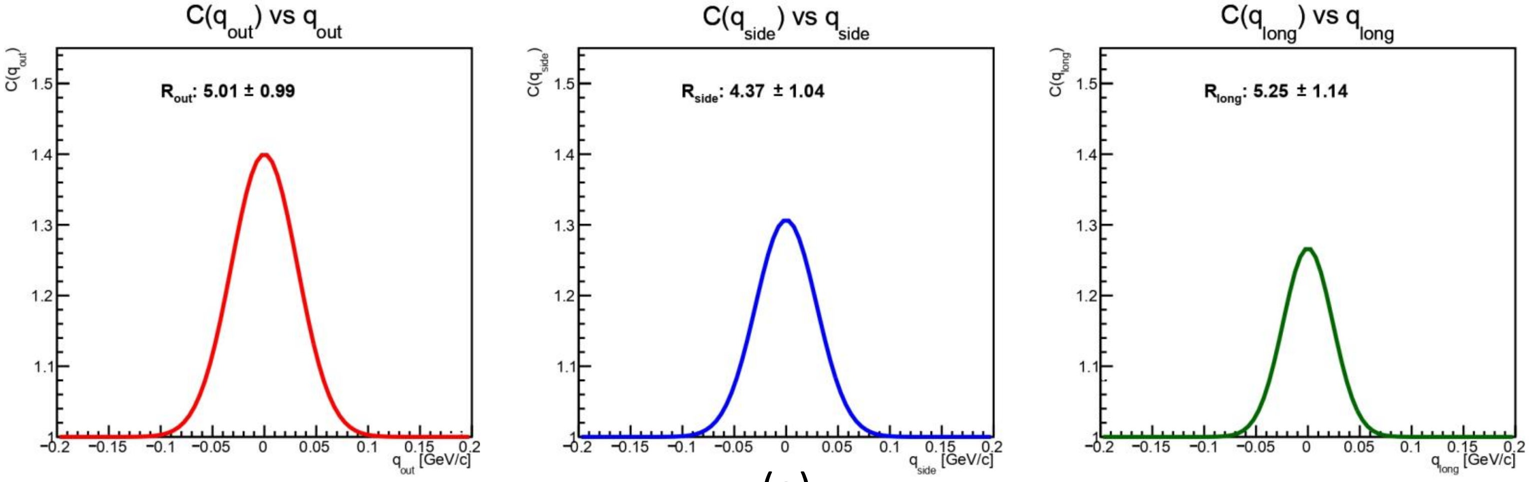
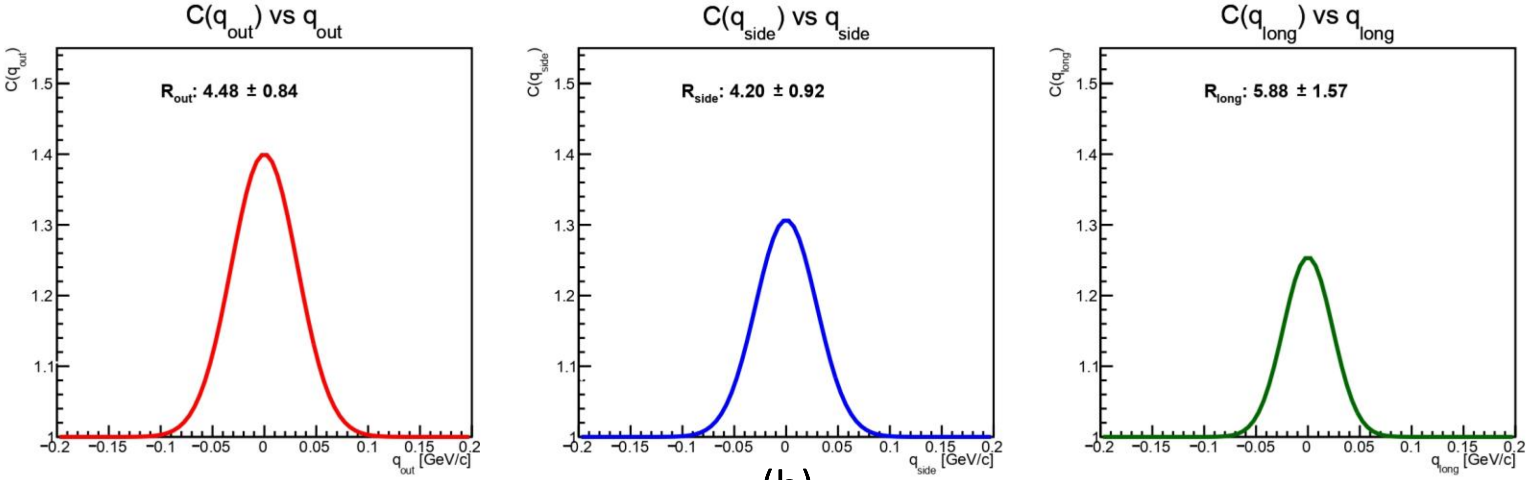


Fig: The 3-D C(q) vs q plots for 0-10% centrality Au-Au collisions at $\sqrt{s_{NN}} = 200\ GeV$.
$0.1\ GeV/c < k_T < 1.0\ GeV/c$; $|y| < 1.0$
(a) For $\pi^+\pi^+$ pairs, (b) For $\pi^-\pi^-$ pairs; (c) For $\kappa^+\kappa^+$ pairs; (d) For $\kappa^-\kappa^-$ pairs

Correlation Function Plots for Protons & Anti-Protons



(a)



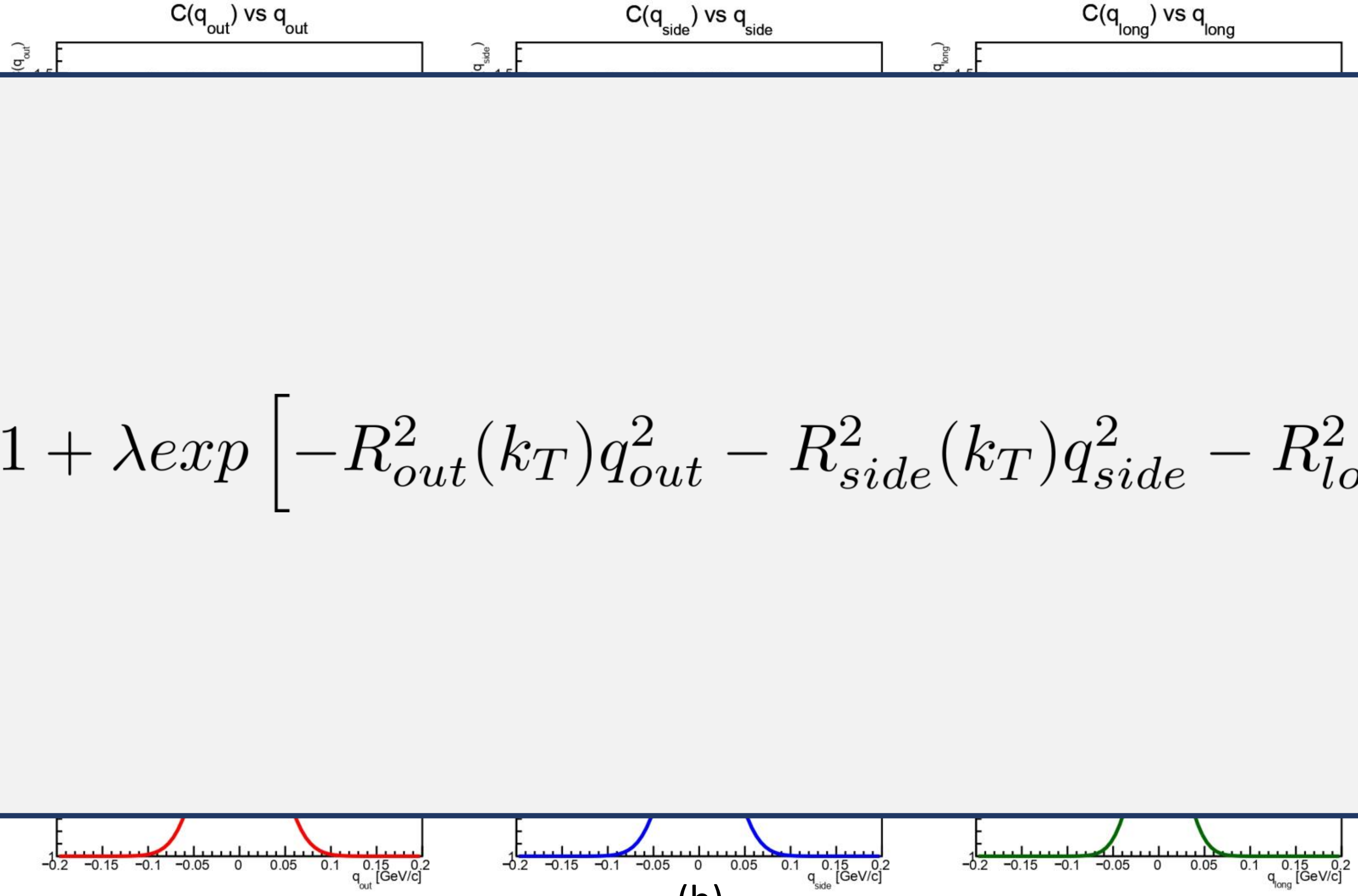
(b)

Fig: The 3-D C(q) vs q plots for 0-10% centrality Au-Au collisions at $\sqrt{s_{NN}} = 200\ GeV$.

$0.1\ GeV/c < k_T < 1.0\ GeV/c$; $|y| < 1.0$

(a) For pp pairs, (b) For $\bar{p}\bar{p}$ pairs

Correlation Function Plots for Protons & Anti-Protons



$$C(q, k_T) = 1 + \lambda exp\left[-R^2_{out}(k_T)q^2_{out} - R^2_{side}(k_T)q^2_{side} - R^2_{long}(k_T)q^2_{long}\right]$$

(b)

Fig: The 3-D C(q) vs q plots for 0-10% centrality Au-Au collisions at $\sqrt{s_{NN}} = 200\ GeV$.

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HBT Radii Distribution for Pions & Kaons

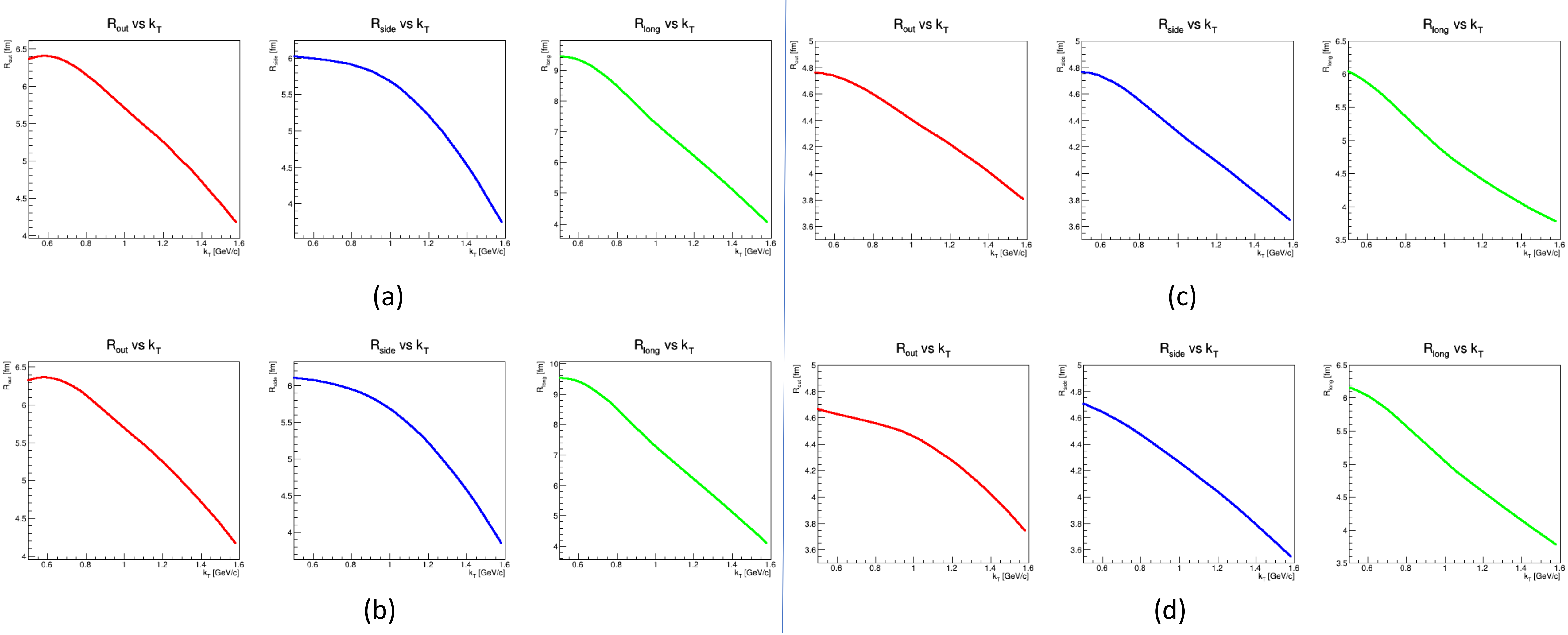

Fig: The three HBT Radii vs k_T plots for 0-10% centrality Au-Au collisions at $\sqrt{s_{NN}} = 200\ GeV$.

$0.02\ GeV/c < k_T < 2.0\ GeV/c$; $|y| < 1.0$

(a) For $\pi^+\pi^+$ pairs, (b) For $\pi^-\pi^-$ pairs; (c) For $\kappa^+\kappa^+$ pairs; (d) For $\kappa^-\kappa^-$ pairs

HBT Radii Distribution for Protons & Anti-Protons

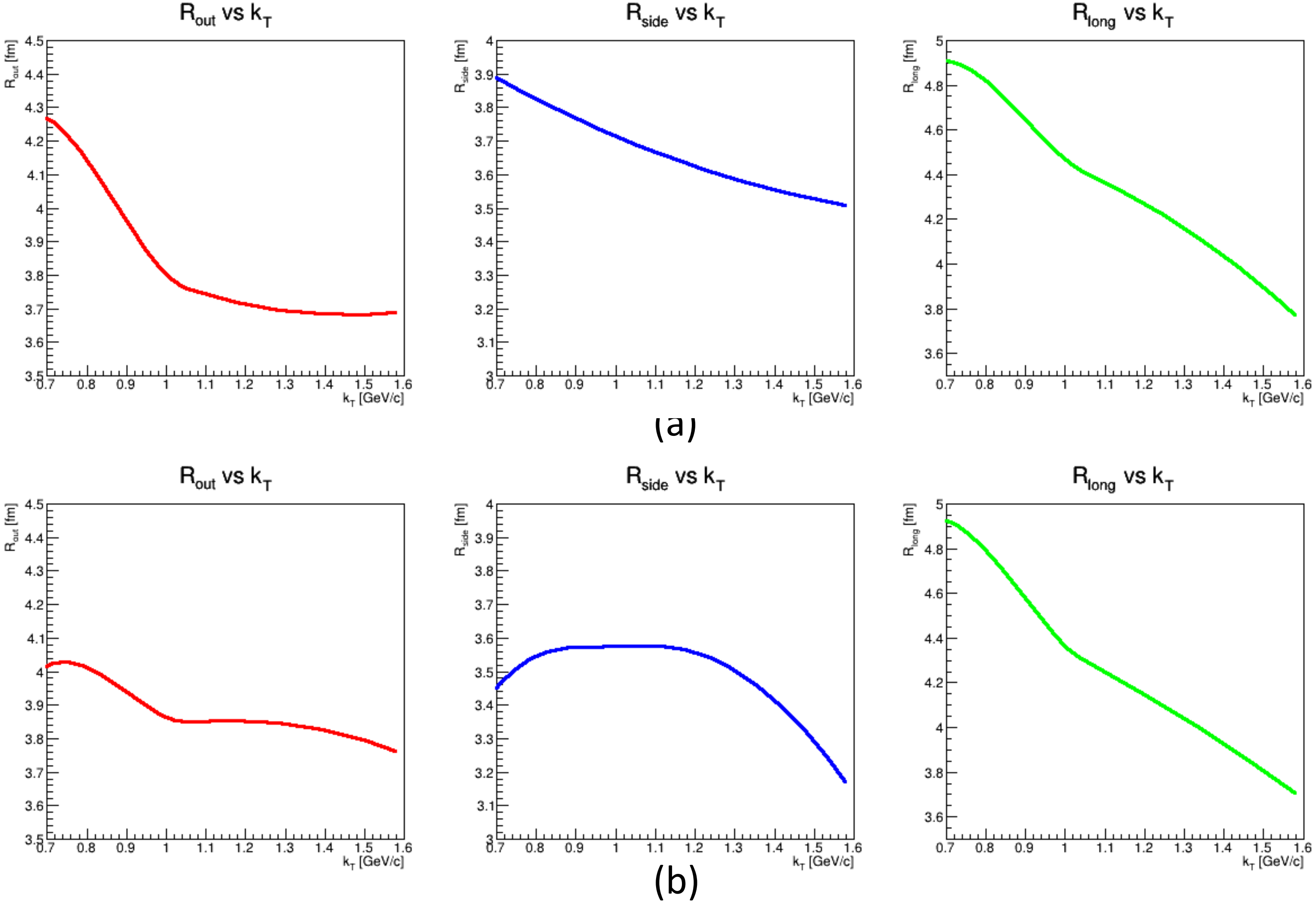

Fig: The three HBT radii vs k_T plots for 0-10% centrality Au-Au collisions at $\sqrt{s_{NN}} = 200\ GeV$.

$0.02\ GeV/c < k_T < 2.0\ GeV/c$; $|y| < 1.0$

(a) For pp pairs, (b) For $\bar{p}\bar{p}$ pairs

Summary

- Calculated 3-D correlation functions for various meson, baryon and anti-baryon pairs.
- Extracted the three HBT Radii and visualized its trend with k_T for different particle pairs.
- Significant Baryon-antibaryon splitting in HBT radii observed at $\sqrt{s_{NN}} = 200$ GeV.

Upcoming Work:

- Calculate the HBT Radii at lower collision energies.
- Study centrality dependence of HBT Radii.
- Explore azimuthally-sensitive HBT Radii [*arXiv:2410.15134(2024)*].

Thank You

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