.

Underlying events in pp collisions at $\sqrt{s} = 13$TeV

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[1] *21d170004*
[2] *210260051*
[3] *210260007*
[4] *210260057*
[5] *210260059*
[6] *210260030*
[7] *210110037*
[8] *210260002*
[9] *210260003*

The underlying event is a particle production not associated with the leading hardest parton-parton process. It is an important element of the hadronic environment within which all physics at the LHC will take place. In order to explore the multiplicity, azimuthal angle, and pseudo-rapidity observed in the numerous underlying events, this article analyses data from a collision system. For the analysis, we begin with various subsets of occurrences having five multiplicity classes. Based on the azimuthal angle ϕ to the direction of the leading jet, we split the particle distribution into three regions: toward, transverse, and away. The Toward and Away regions contain the fragmentation products of the hard scatterings in addition to the contribution of the underlying event, whereas particles in the Transverse region are expected to originate predominantly from the underlying events. Our goal is to deduce how variables' trends have changed in relation to changes in different azimuthal regions defined with respect to the leading particle direction and over different multiplicity classes.

I. INTRODUCTION

The data provided is generated with Pythia 8 Monte Carlo event generator.
Number of events: 2 million
Collisions System : p + p at center of mass energy 13 TeV.

We begin with defining the kinematic variables used to study the underlying events:

- **Multiplicity:** The quantity of newly created particles produced in a specific proton-proton collision. An important observable that captures the characteristics of the hot, dense system created in the region where the two arriving nuclei merge is the multiplicity. The total multiplicity of charged particles, their distribution in pseudo-rapidity space (angular dependence), and their dependence on collision centrality and energy can all be measured; even without more precise and differentiated measurements of the emitted particles, one can still learn crucial details about the collision from these measurements.

- **Pseudo-rapidity(η):** In experimental physics, it is the spatial coordinate describing the angle of a particle relative to the beam axis. It is defined as:

  $$\eta = \text{-}\ln \tan(\theta/2)$$

  where θ is the angle formed by the particle's three-momentum p and the beam axis's positive direction. In hadron colliders like the LHC, where interactions seldom have their centre of mass frame overlap with the detector rest frame due to the composite nature of colliding particles, pseudo-rapidity is very helpful because it makes estimating much quicker and simpler.

- **Transverse momentum(pT):** the part of momentum that is transverse(perpendicular) to the beam line. It is significant because, unlike transverse momentum, which is always linked to the physics occurring at the vertex, momentum along the beam line may simply be leftover from beam particles.

The traditional approach used to study the observables sensitive to UE is on an event by event basis. In this approach, the leading particle (particle with highest pT) is used to segment the $\eta - \phi$ space into three distinct regions based on the azimuthal angular difference $\Delta\phi$ relative to the leading particle which acts as a proxy for the main flow

of hard-scattering process. The azimuthal angular difference is defined as, $\Delta\phi = |\phi - \phi_L|$, where ϕ is the azimuthal angle of an outgoing charged particle in an event and ϕ_L is the azimuthal angle of the charged particle having highest transverse momentum in the event. The toward region of is defined as $|\Delta\phi| < 60°$ and the away region is defined as $|\Delta\phi| > 120°$. The transverse region is defined as $60° < |\Delta\phi| < 120°$.

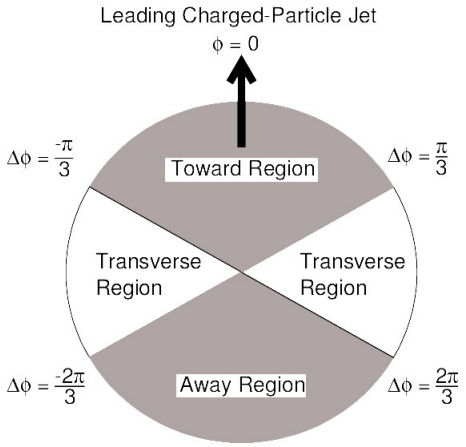

Fig 0(a): Division of ϕ into toward, away and transverse regions.

II. EXPERIMENTAL OBSERVATIONS

Distribution of kinematic observables for different multiplicity classes (0-20, 20-40 etc).

1. Plots for pseudo-rapidity(η) distribution (Number of particles versus η) in the three regions: towards, transverse, away. For these plots, the region from -3 to 3 has been divided into 100 sections.

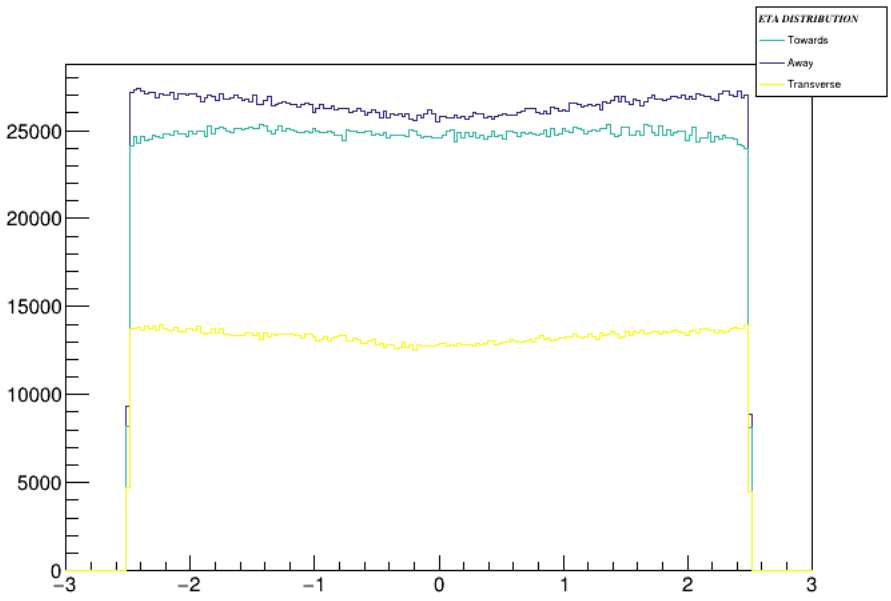

Fig 1(a): η-distribution with multiplicity class 0-20

	Toward	Transverse	Away
Entries	4139133	2218033	4411148
Mean	-0.002062	-0.002024	-0.002466
Standard Deviation	1.442	1.458	1.454

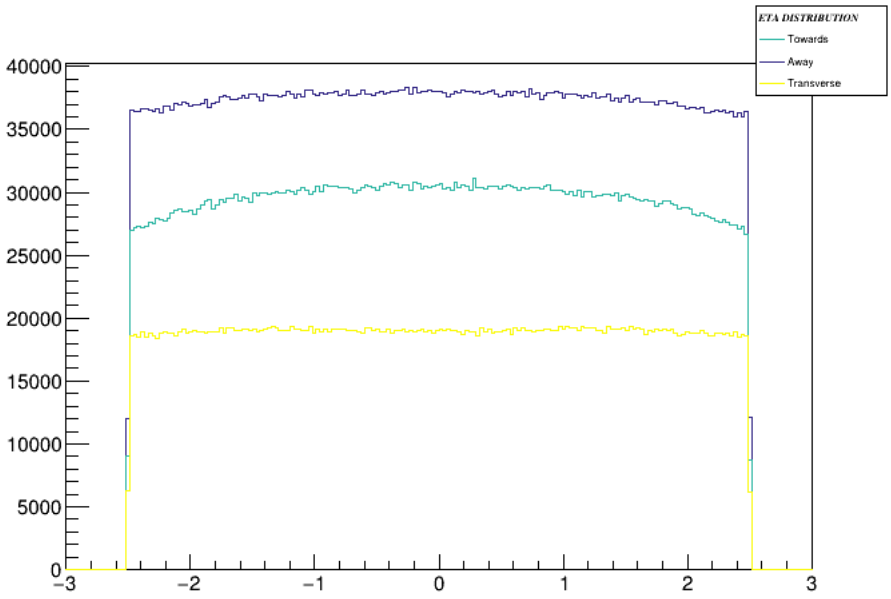

Fig 1(b): η-distribution with multiplicity class 20-40

	Toward	Transverse	Away
Entries	4925680	3163416	6244580
Mean	-0.0008528	-8.936e-05	-0.002603
Standard Deviation	1.421	1.434	1.44

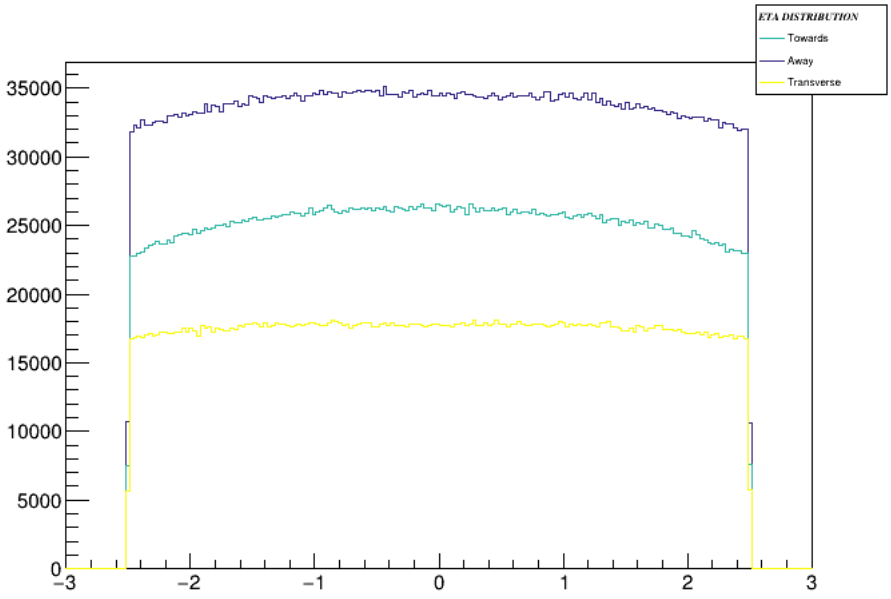

Fig 1(c): η-distribution with multiplicity class 40-60

	Toward	Transverse	Away
Entries	4215595	2928271	5648114
Mean	-0.002388	-0.002187	-0.003846
Standard Deviation	1.418	1.433	1.428

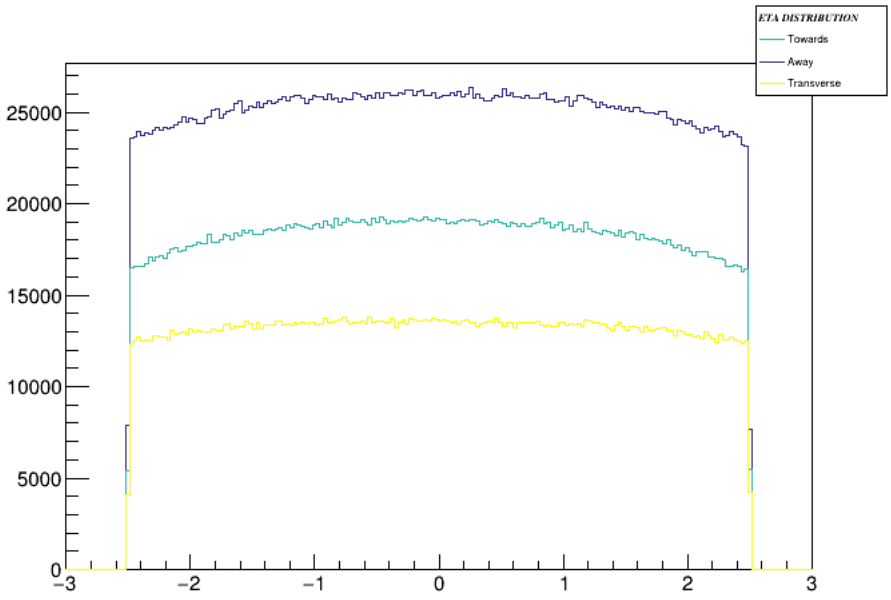

Fig 1(d): η-distribution with multiplicity class 60-80

	Toward	Transverse	Away
Entries	3053479	2209126	4207882
Mean	-0.003725	-0.003211	-0.003041
Standard Deviation	1.416	1.427	1.424

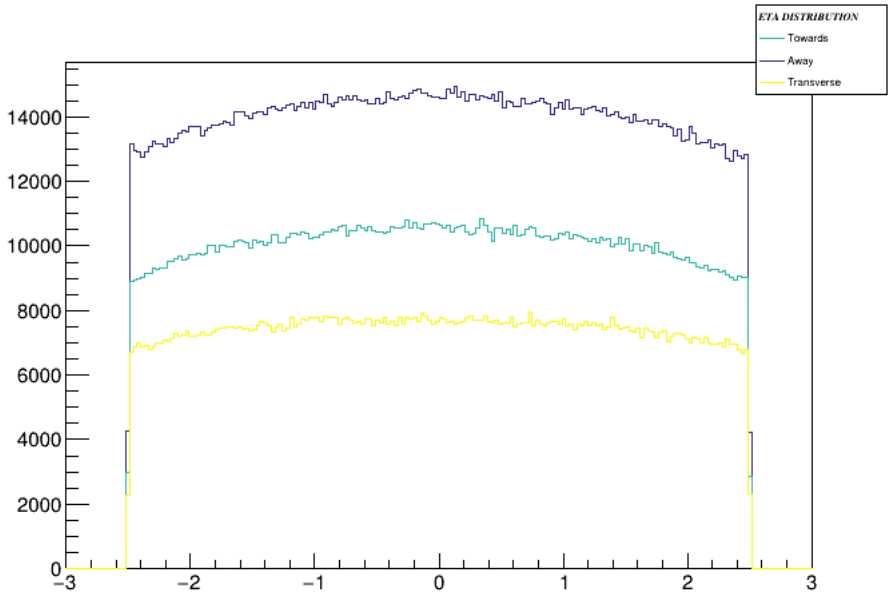

Fig 1(e): η-distribution with multiplicity class 80-100

	Toward	Transverse	Away
Entries	1679598	1241991	2341633
Mean	-0.004794	-0.004341	-0.003978
Standard Deviation	1.412	1.42	1.417

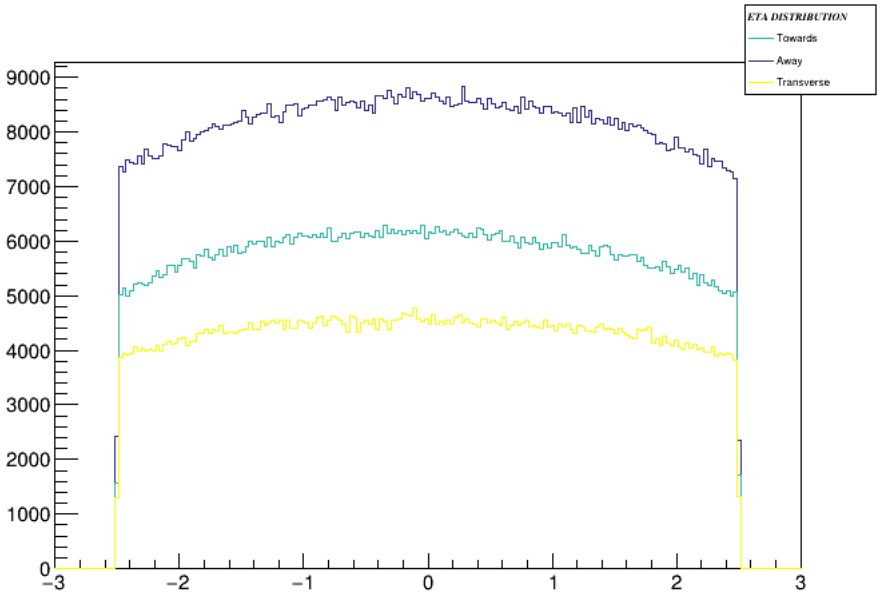

Fig 1(f): η-distribution with multiplicity class 100 and above

	Toward	Transverse	Away
Entries	969402	725731	1364341
Mean	-0.008361	-0.005366	-0.004674
Standard Deviation	1.406	1.414	1.411

2. Plots for multiplicity distribution (Number of events versus number of particles produced). For these plots, the region from 0 to 250 has been divided into 100 sections.

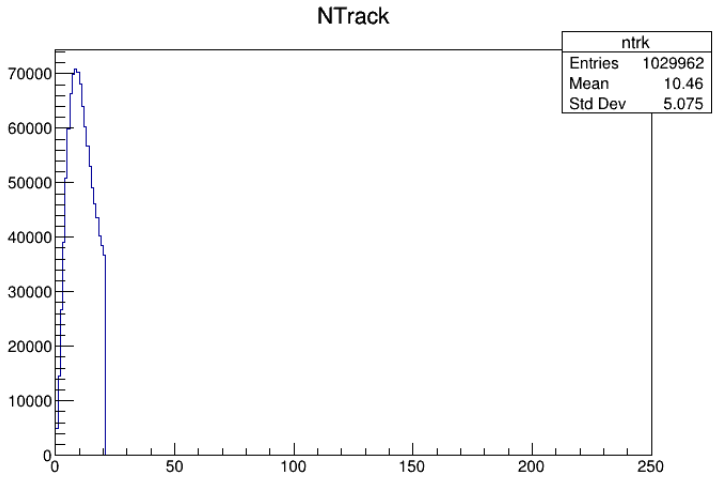

Fig 2(a): NTRK-distribution with multiplicity class 0-20

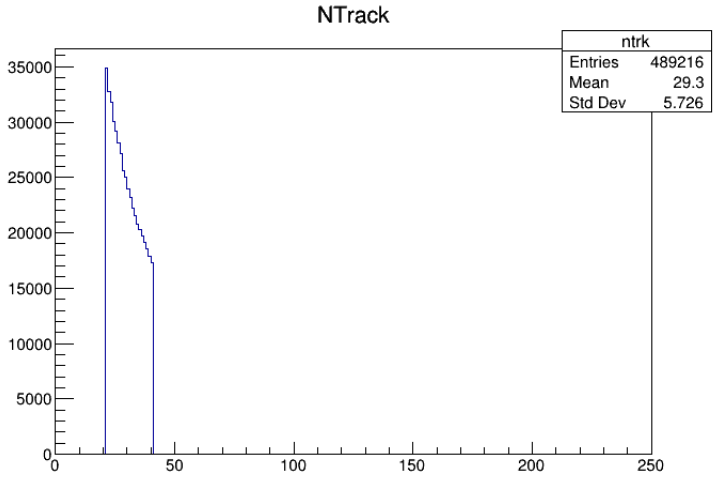

Fig 2(b): NTRK-distribution with multiplicity class 20-40

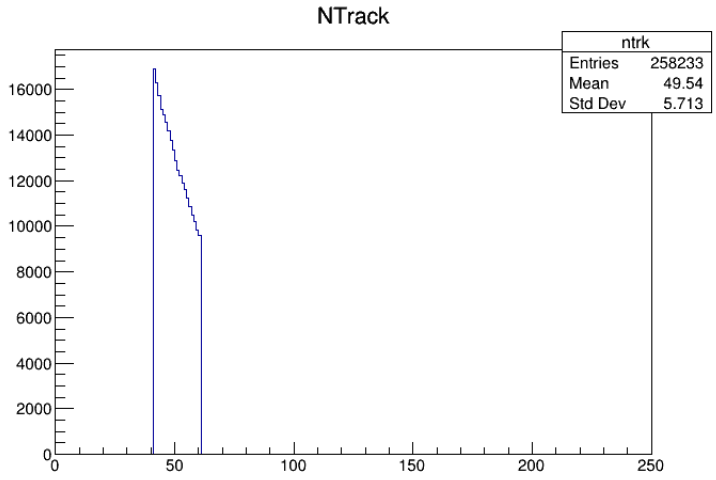

Fig 2(c): NTRK-distribution with multiplicity class 40-60

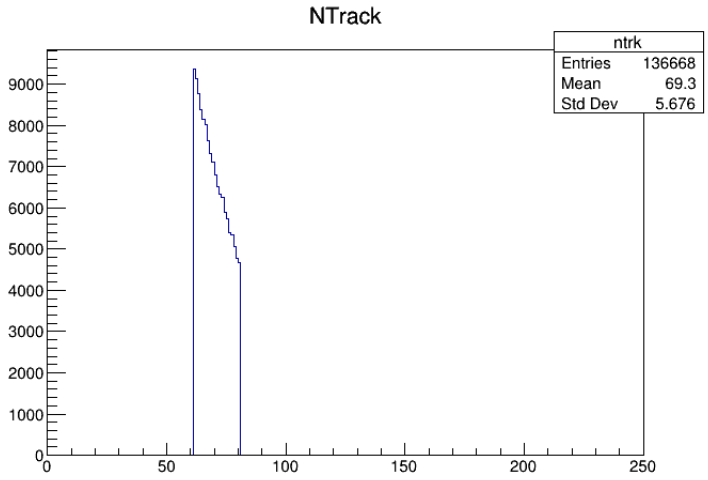

Fig 2(d): NTRK-distribution with multiplicity class 60-80

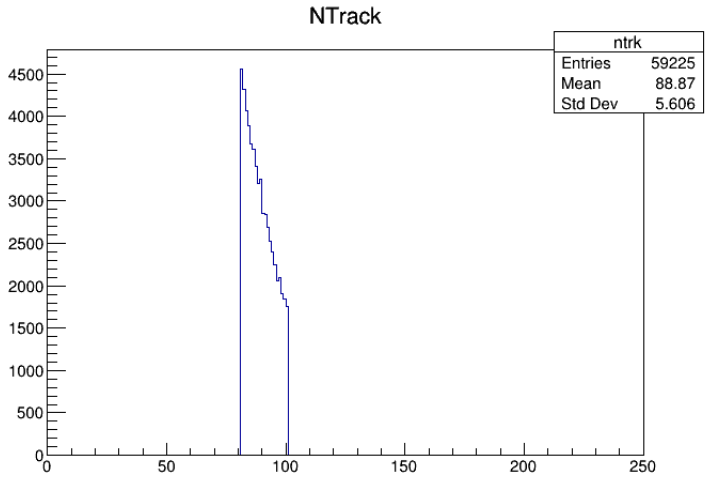

Fig 2(e): NTRK-distribution with multiplicity class 80-100

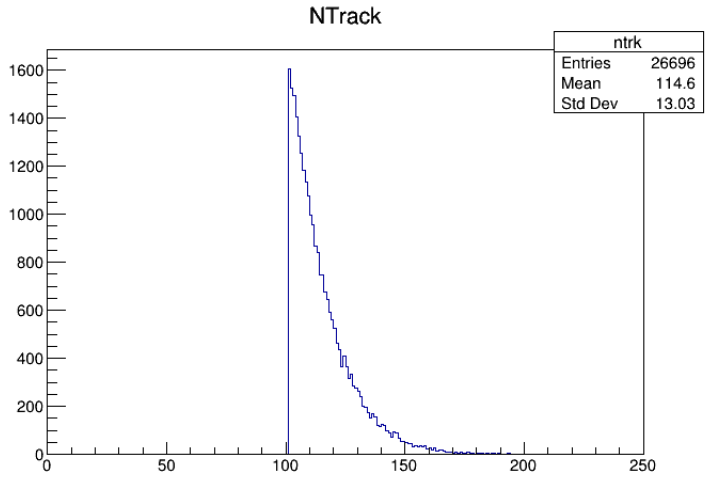

Fig 2(f): NTRK-distribution with multiplicity class 100 onwards

3. Plots for azimuthal angle distribution with different multiplicities in towards, transverse and away regions. For these plots, the region from -4 to 4 has been divided into 100 sections.

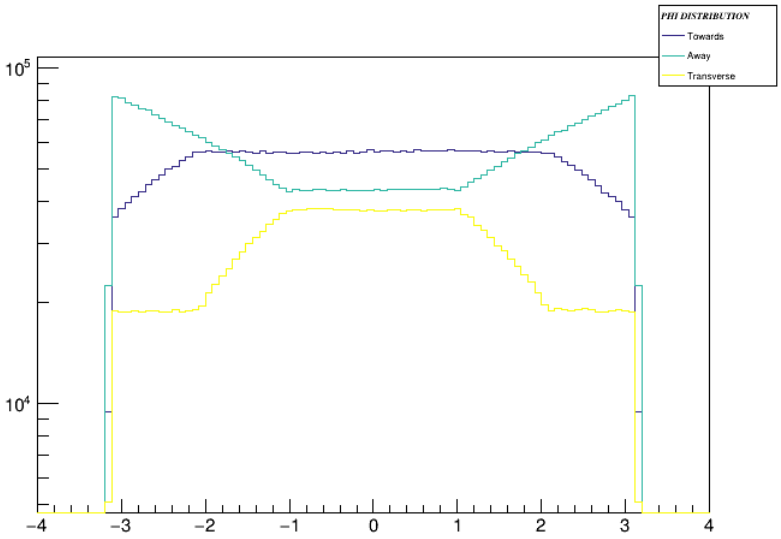

Fig 3(a): ϕ-distribution with multiplicity class 0-20

	Toward	Transverse	Away
Entries	4139133	2218033	4411148
Mean	0.0004138	0.001404	-0.005153
Standard Deviation	1.728	1.581	1.993

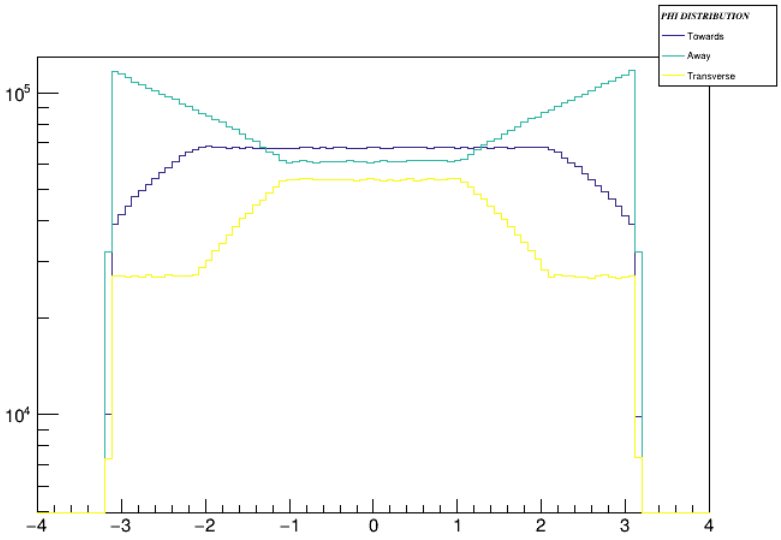

Fig 3(b): ϕ-distribution with multiplicity class 20-40

	Toward	Transverse	Away
Entries	4925680	3163416	6244580
Mean	-0.001788	-0.0008991	0.001791
Standard Deviation	1.714	1.581	1.993

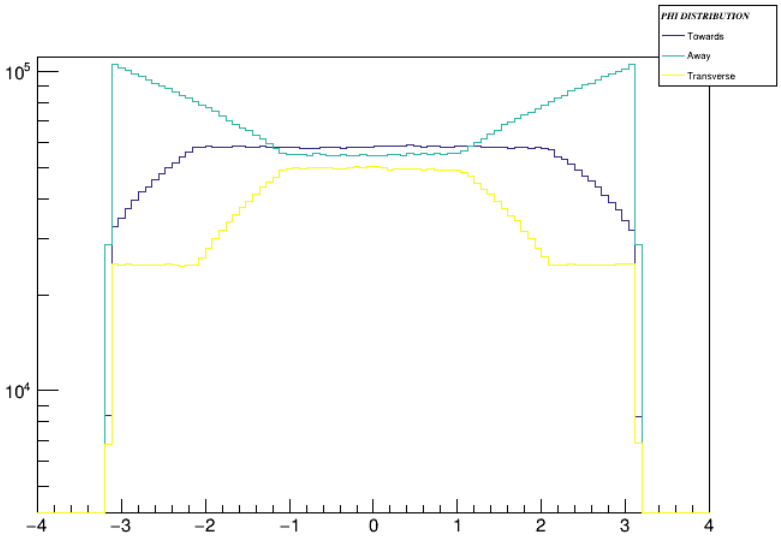

Fig 3(c): ϕ-distribution with multiplicity class 40-60

	Toward	Transverse	Away
Entries	4215595	2928271	5648114
Mean	-0.004931	-0.002353	0.002018
Standard Deviation	1.706	1.58	1.995

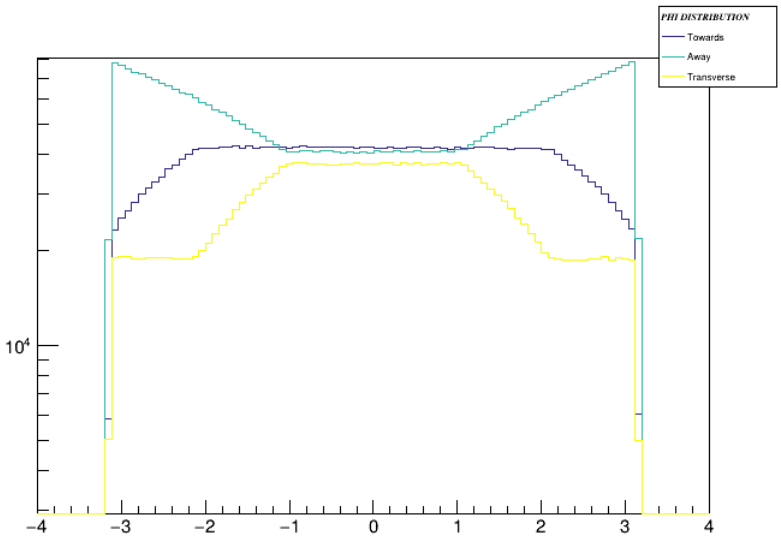

Fig 3(d): ϕ-distribution with multiplicity class 60-80

	Toward	Transverse	Away
Entries	3053479	2209126	4207882
Mean	-0.002271	-0.001026	0.001731
Standard Deviation	1.704	1.582	1.996

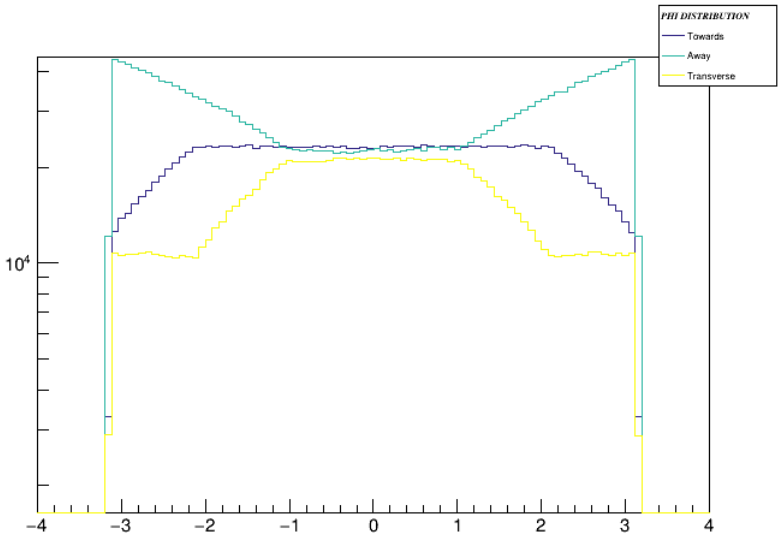

Fig 3(e): ϕ-distribution with multiplicity class 80-100

	Toward	Transverse	Away
Entries	1679598	1241991	2341633
Mean	-0.001019	-0.0003573	-0.0009784
Standard Deviation	1.701	1.583	1.999

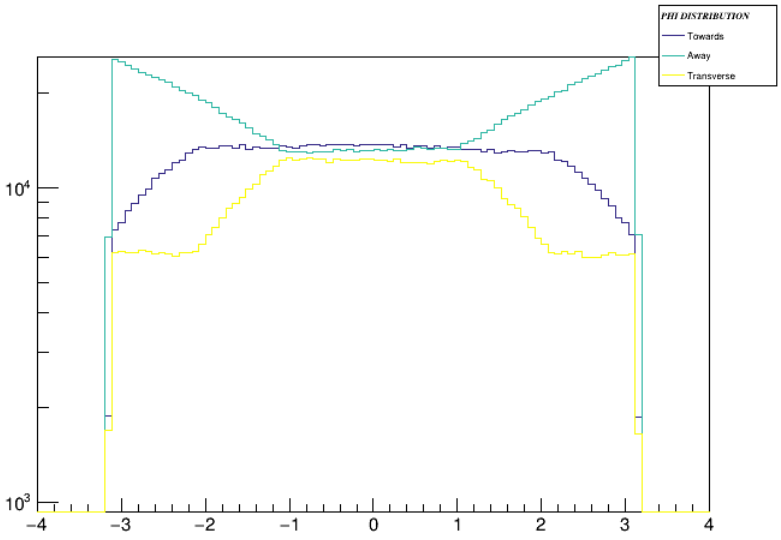

Fig 3(f): ϕ-distribution with multiplicity class 100 onward

	Toward	Transverse	Away
Entries	969402	725731	1364341
Mean	-0.01801	-0.007086	0.01229
Standard Deviation	1.696	1.584	2.001

4. Plots for charged particle multiplicity as a function of pT in towards, transverse and away regions. For these plots, the region from 0 to 75 has been divided into 100 sections. The Y-axis has been represented using the log-scale.

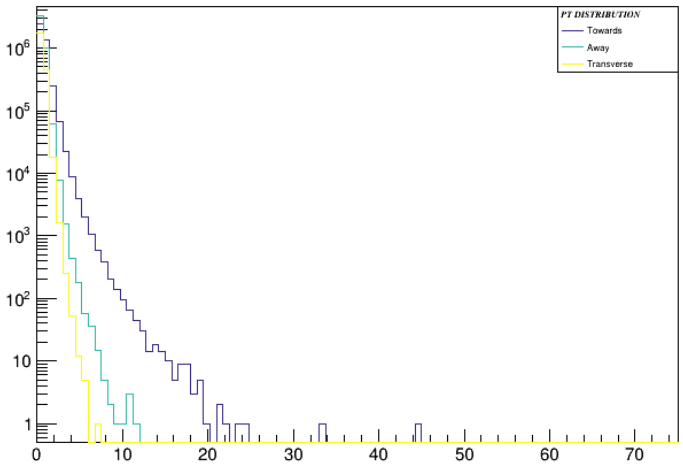

Fig 4(a): pT-distribution with multiplicity class 0-20

	Toward	Transverse	Away
Entries	4139133	2218033	4411148
Mean	0.8399	0.63	0.6552
Standard Deviation	0.5497	0.2294	0.2692

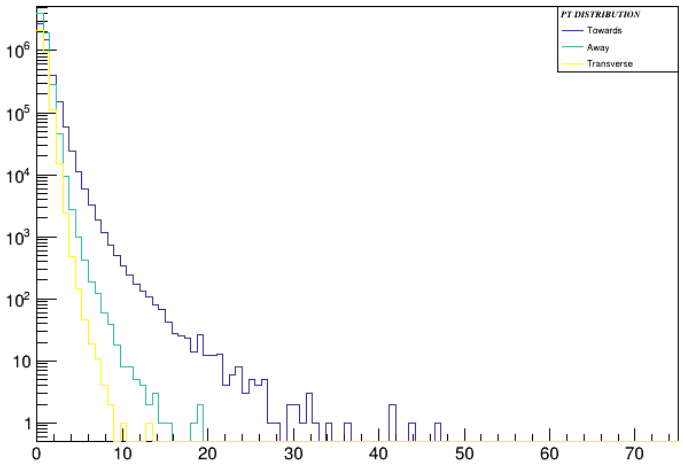

Fig 4(b): pT-distribution with multiplicity class 20-40

	Toward	Transverse	Away
Entries	4925680	3163416	6244580
Mean	0.9413	0.7339	0.7674
Standard Deviation	0.7336	0.3505	0.3975

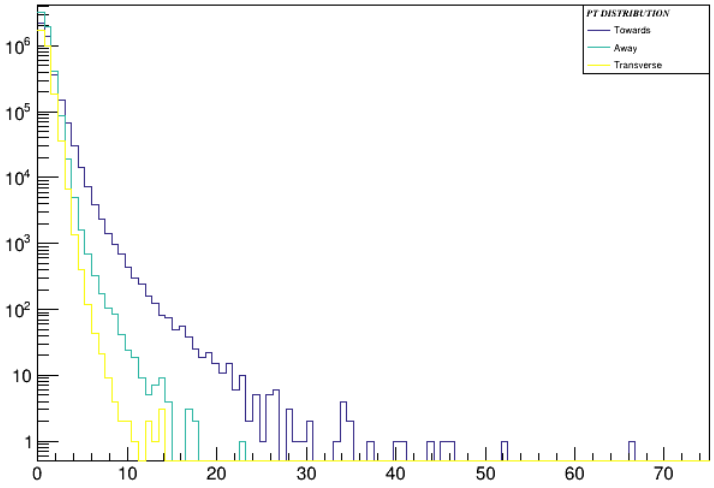

Fig 4(c): pT-distribution with multiplicity class 40-60

	Toward	Transverse	Away
Entries	4215595	2928271	5648114
Mean	0.999	0.818	0.8468
Standard Deviation	0.8188	0.4443	0.4846

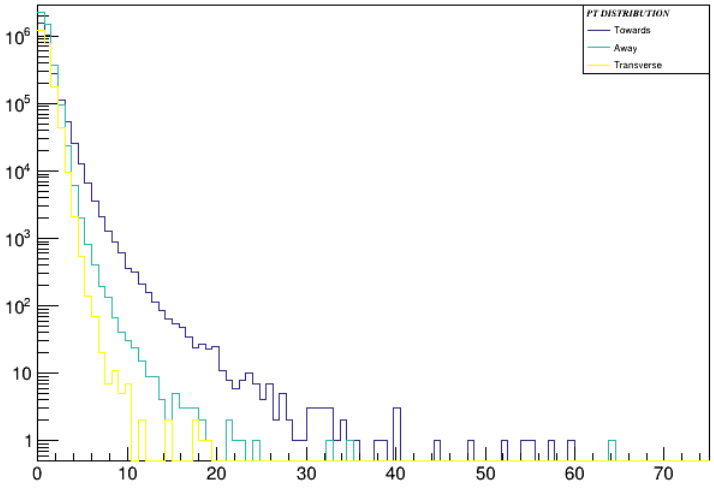

Fig 4(d): pT-distribution with multiplicity class 60-80

	Toward	Transverse	Away
Entries	3053479	2209126	4207882
Mean	1.035	0.8735	0.8993
Standard Deviation	0.8742	0.5068	0.5463

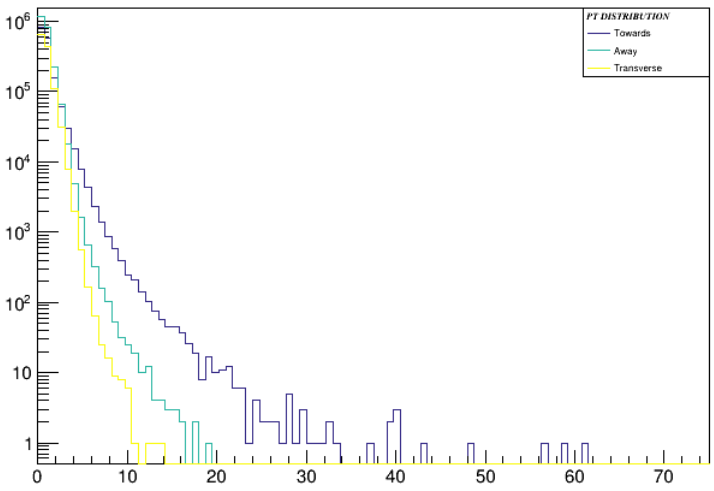

Fig 4(e): pT-distribution with multiplicity class 80-100

	Toward	Transverse	Away
Entries	1679598	1241991	2341633
Mean	1.058	0.9106	0.9353
Standard Deviation	0.9119	0.5515	0.5881

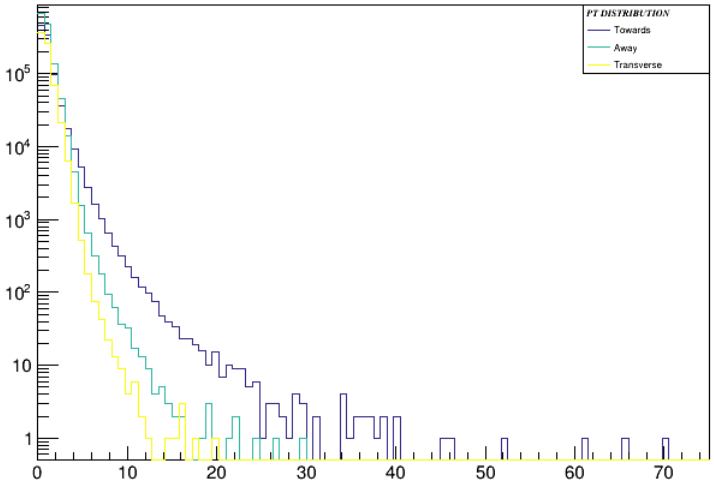

Fig 4(f): pT-distribution with multiplicity class 100 onwards

	Toward	Transverse	Away
Entries	969402	725731	1364341
Mean	b 1.081	0.9394	0.9684
Standard Deviation	c 0.9853	0.5942	0.6415

5. Plots for pT-distribution in different azimuthal regions across all multiplicity classes.

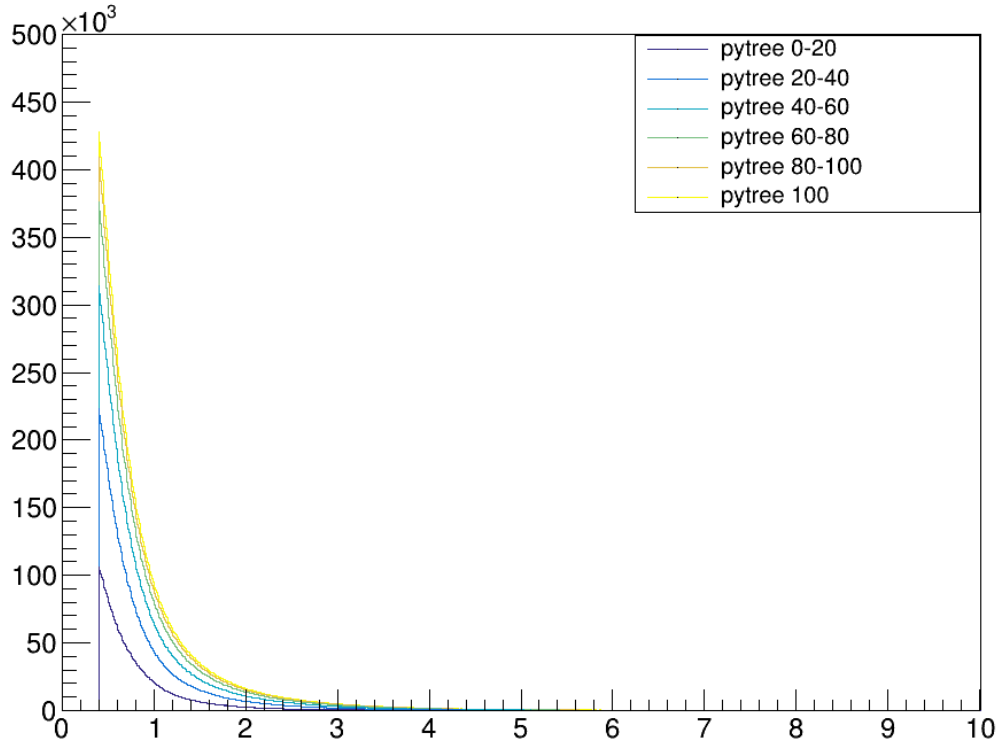

Fig 5(a): pT-distribution in towards region across all multiplicity classes

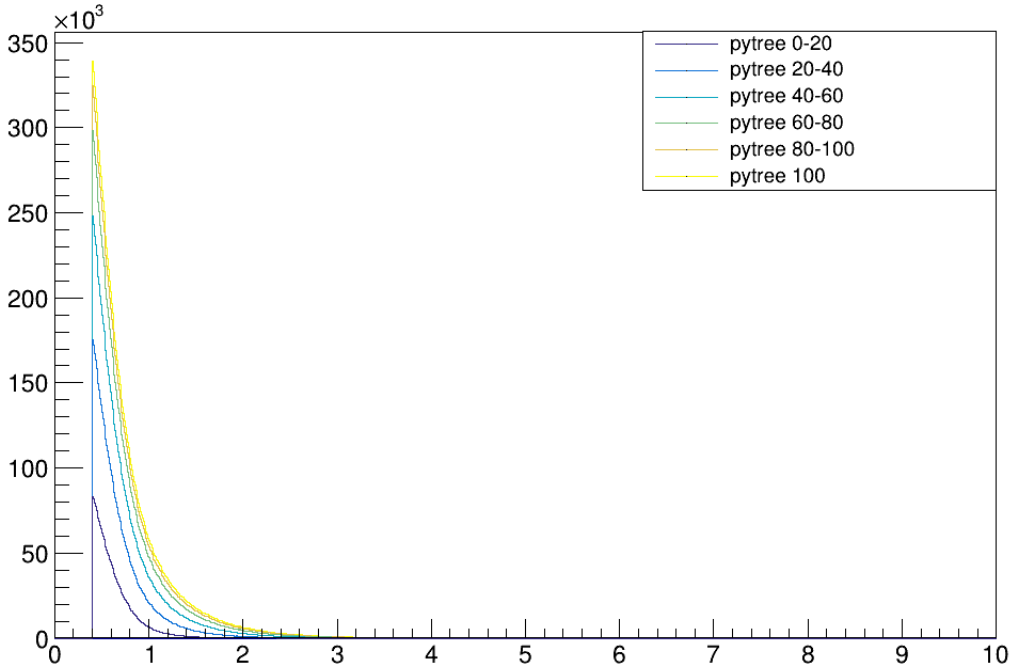

Fig 5(b): pT-distribution in transverse region across all multiplicity classes

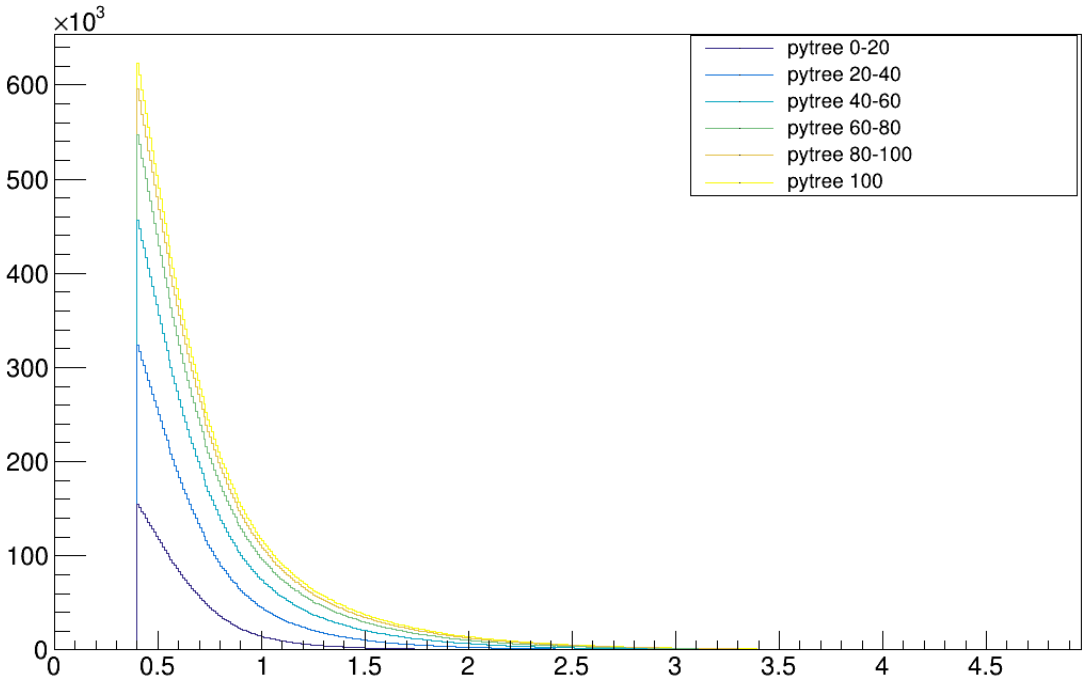

Fig 5(c): pT-distribution in away region across all multiplicity classes

6. The maximum values of pT in a given multiplicity class:

Multiplicity Class	**Maximum value of pT**
$0-20$	44.3555
$20-40$	46.8956
$40-60$	66.4668
$60-80$	89.2544
$80-100$	61.3556
$100-$	137.469

III. Summary

The towards and away regions are dominated by particles produced in hard processes, while the transverse region is more sensitive to underlying events. In this work, an attempt has been made to study the underlying events through the kinematic observables in the three different regions for pp collisions at beam energy $\sqrt{s} = 13$TeV. The study confirms the trend that the charged-particle density in the azimuthal regions(i.e. towards, transverse and away) shows a sharp fall as pT increases, i.e., it rises steeply for low values of pT and reaches a plateau. Here is a link to our code Link

[1] J. Adams *et al.*, (ALICE Collaboration), Nature Physics**13**,535-539 (2017).
[2] S. Dash and K. Kumar, The European Physical Journal A**58** (2022)