

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

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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  $\phi$  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( $\eta$ ):** In experimental physics, it is the spatial coordinate describing the angle of a particle relative to the beam axis. It is defined as:

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

where  $\theta$  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( $p_T$ ):** 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  $p_T$ ) 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  $\phi$  is the azimuthal angle of an outgoing charged particle in an event and  $\phi_L$  is the azimuthal angle of the charged particle having highest transverse momentum in the event. The toward region of is defined as  $|\Delta\phi| < 60^\circ$  and the away region is defined as  $|\Delta\phi| > 120^\circ$ . The transverse region is defined as  $60^\circ < |\Delta\phi| < 120^\circ$ .

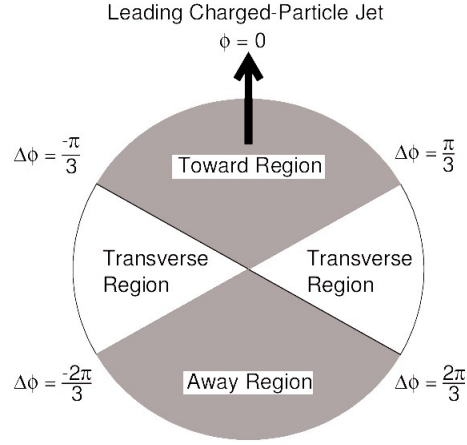


Fig 0(a): Division of  $\phi$  into toward, away and transverse regions.

## II. EXPERIMENTAL OBSERVATIONS

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

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

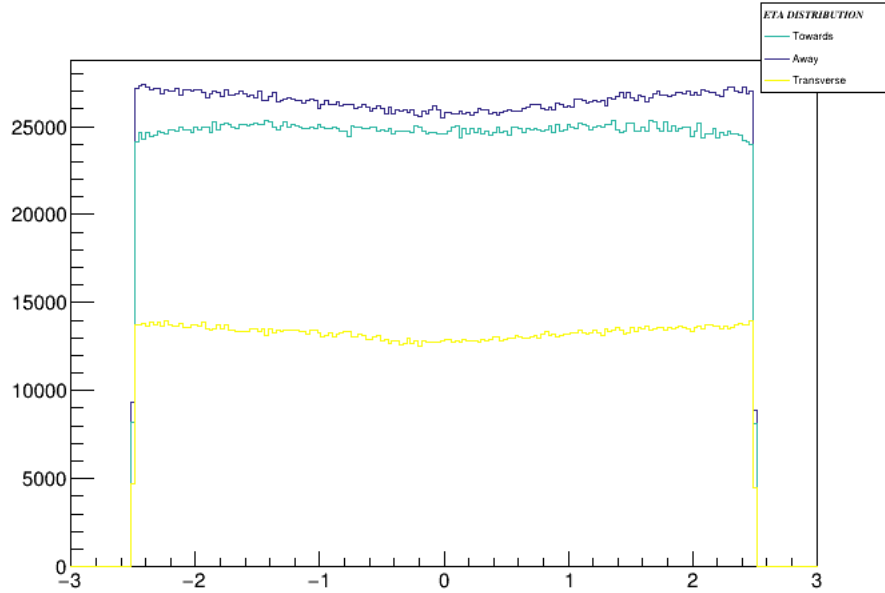


Fig 1(a):  $\eta$ -distribution with multiplicity class 0-20

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

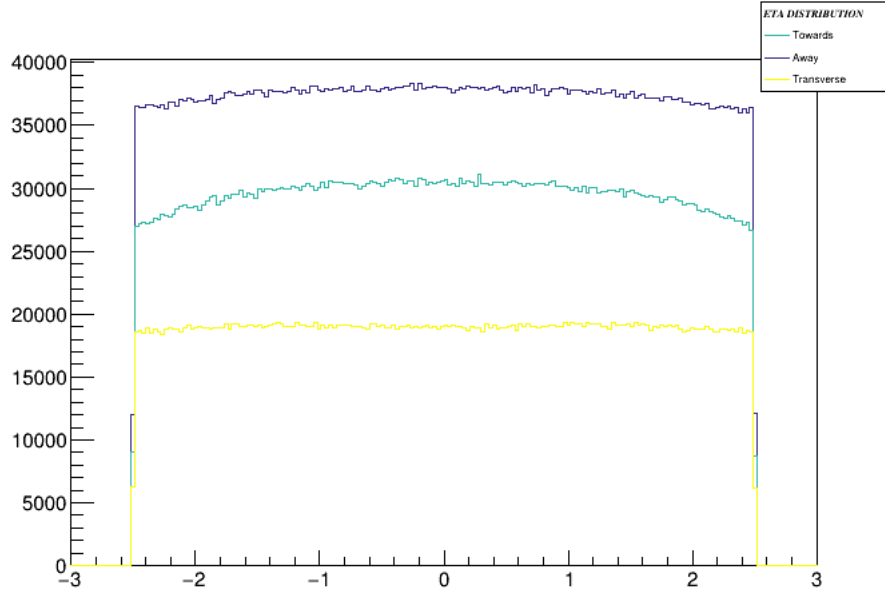


Fig 1(b):  $\eta$ -distribution with multiplicity class 20-40

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

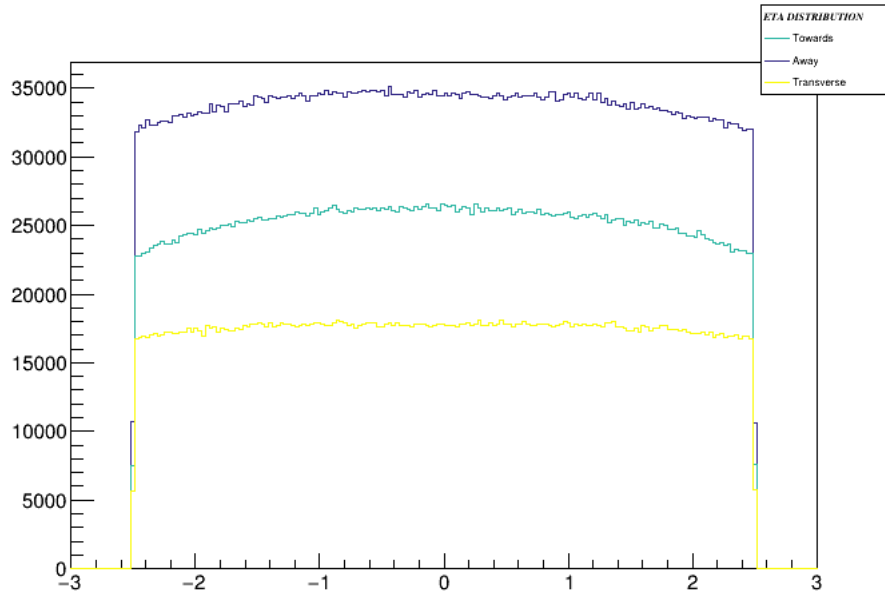


Fig 1(c):  $\eta$ -distribution with multiplicity class 40-60

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

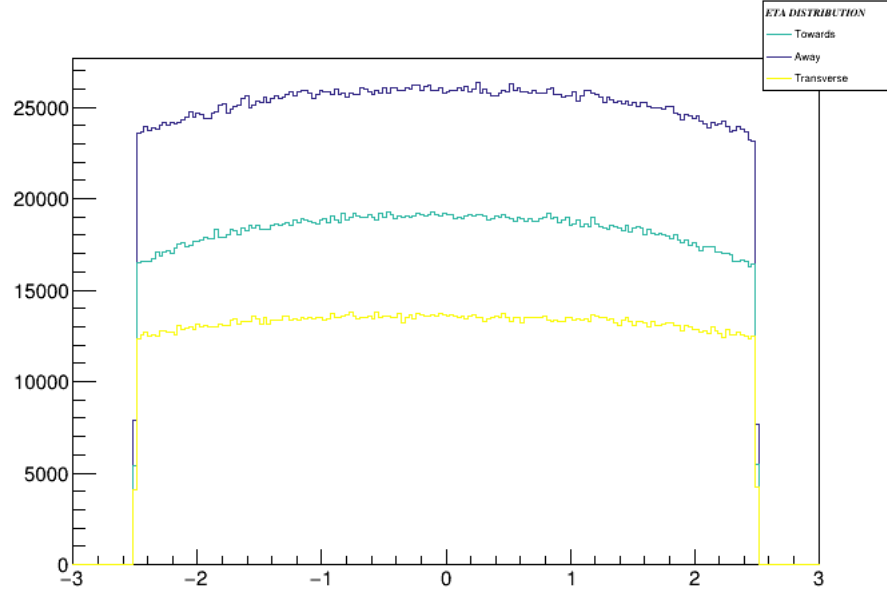


Fig 1(d):  $\eta$ -distribution with multiplicity class 60-80

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

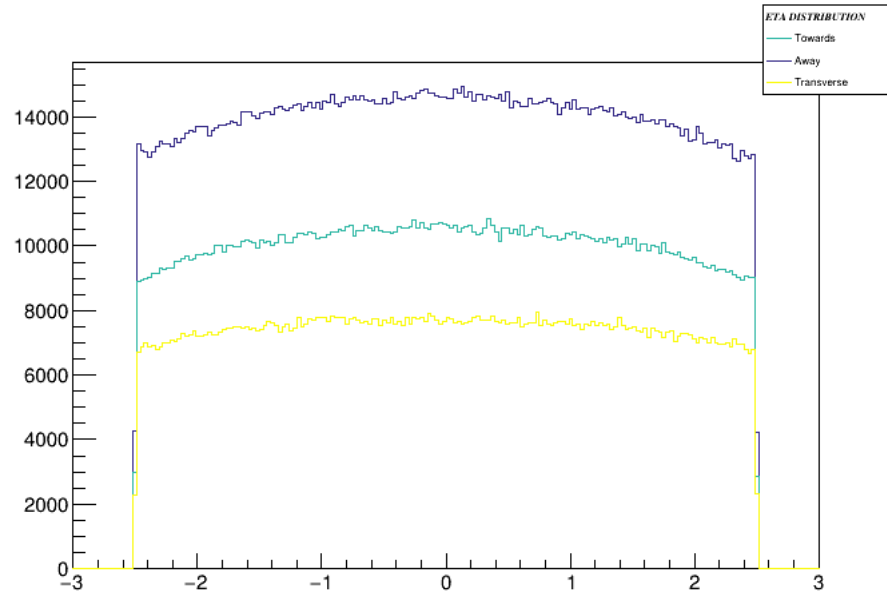


Fig 1(e):  $\eta$ -distribution with multiplicity class 80-100

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

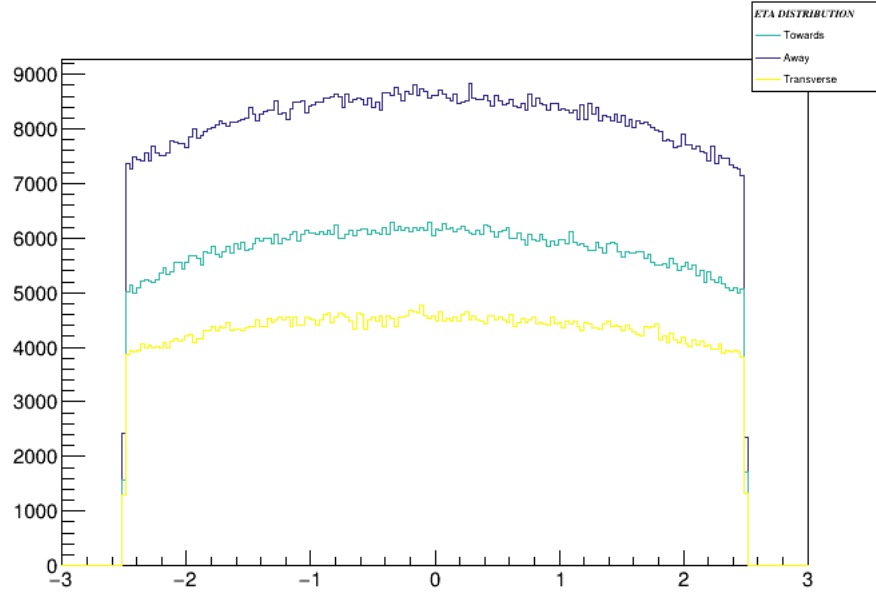


Fig 1(f):  $\eta$ -distribution with multiplicity class 100 and above

	Toward	Transverse	Away
<b>Entries</b>	969402	725731	1364341
<b>Mean</b>	-0.008361	-0.005366	-0.004674
<b>Standard Deviation</b>	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.

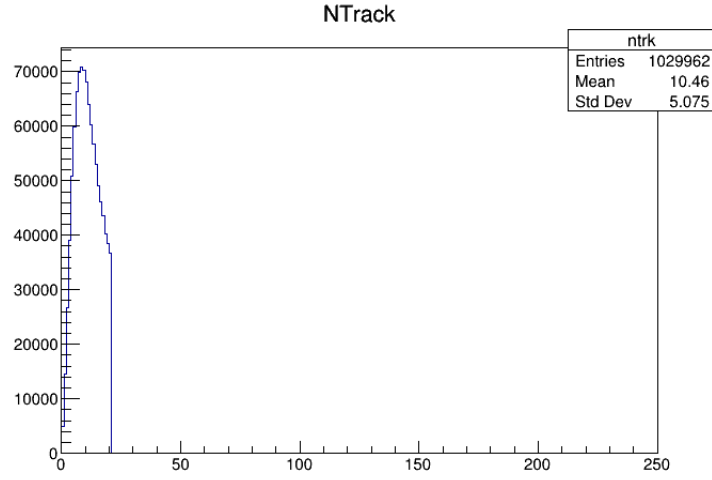


Fig 2(a): NTRK-distribution with multiplicity class 0-20

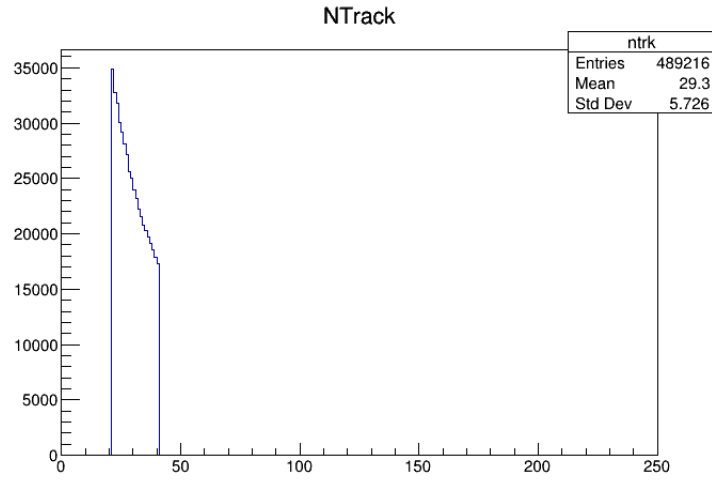


Fig 2(b): NTRK-distribution with multiplicity class 20-40

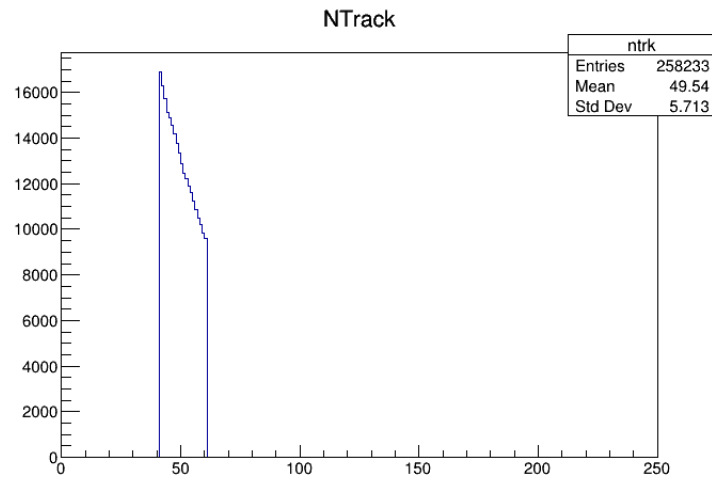


Fig 2(c): NTRK-distribution with multiplicity class 40-60

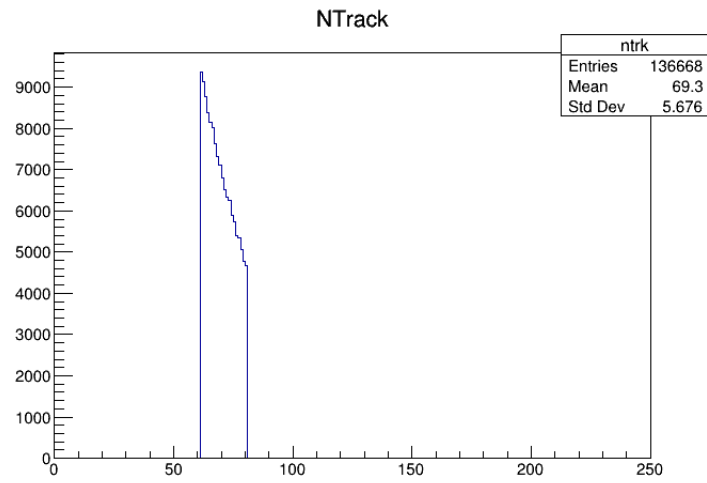


Fig 2(d): NTRK-distribution with multiplicity class 60-80

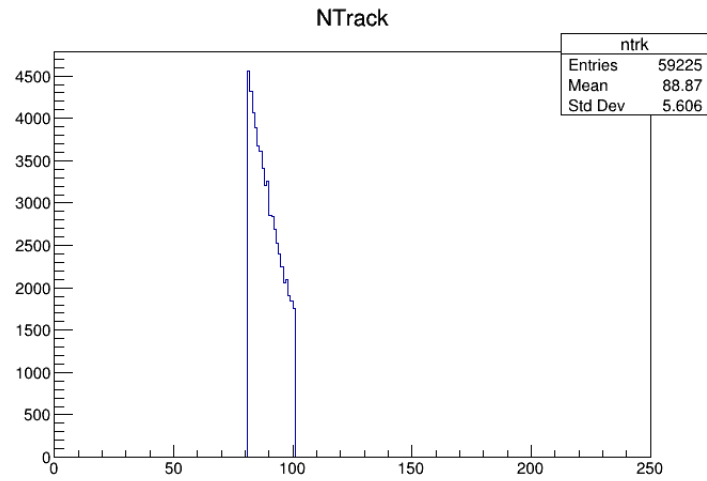


Fig 2(e): NTRK-distribution with multiplicity class 80-100

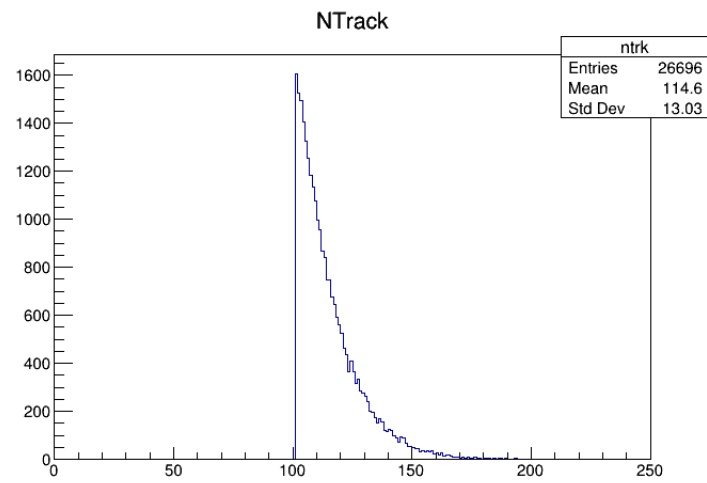


Fig 2(f): NTRK-distribution with multiplicity class 100 onwards

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.

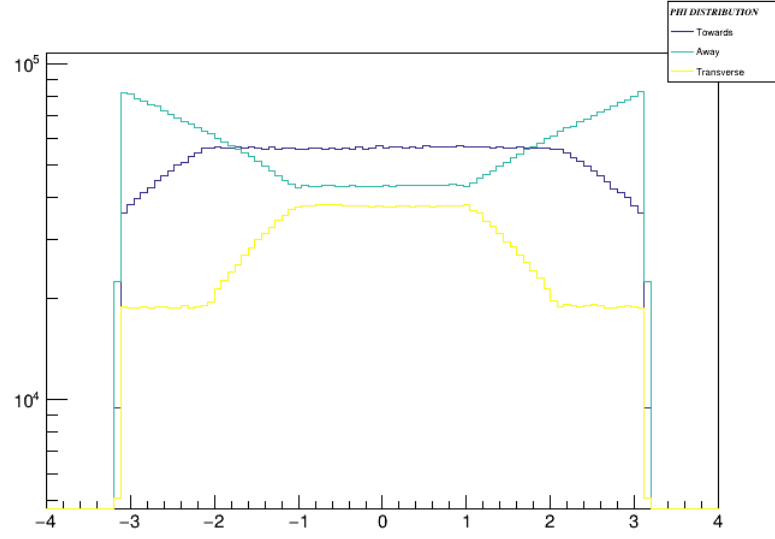


Fig 3(a):  $\phi$ -distribution with multiplicity class 0-20

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

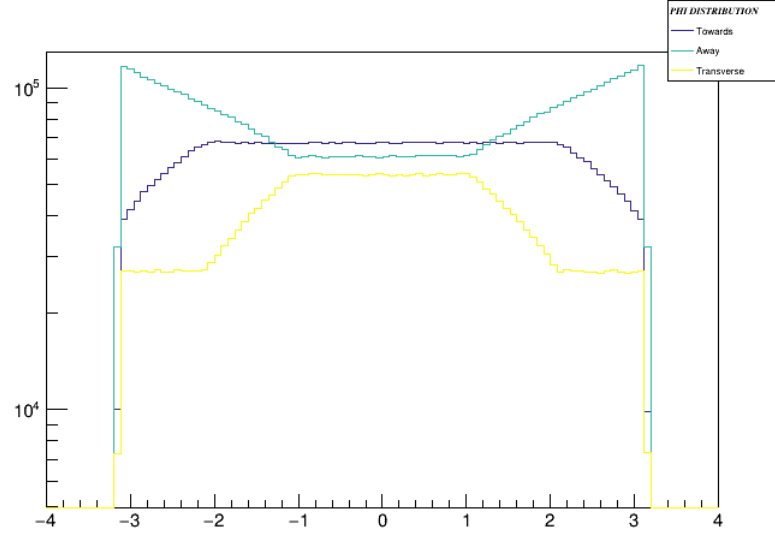


Fig 3(b):  $\phi$ -distribution with multiplicity class 20-40

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



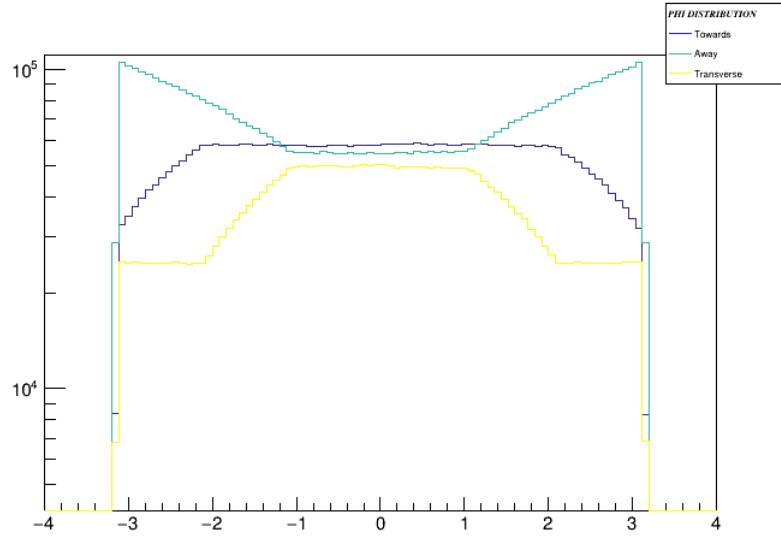


Fig 3(c):  $\phi$ -distribution with multiplicity class 40-60

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

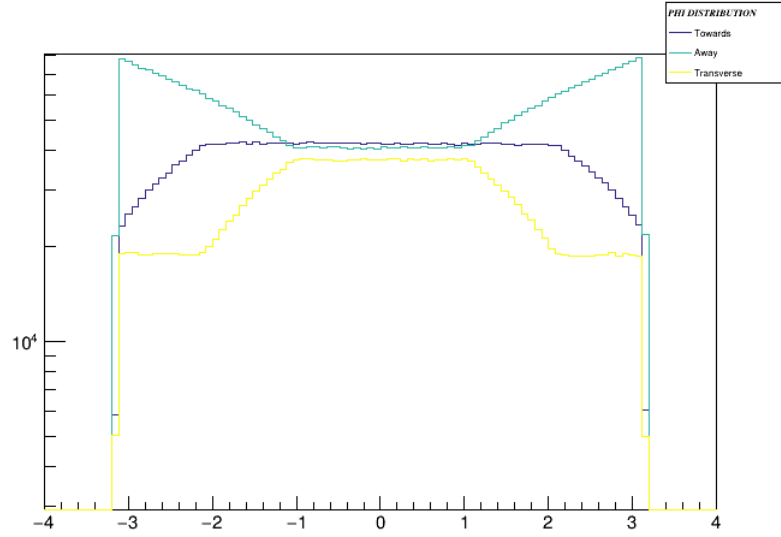


Fig 3(d):  $\phi$ -distribution with multiplicity class 60-80

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

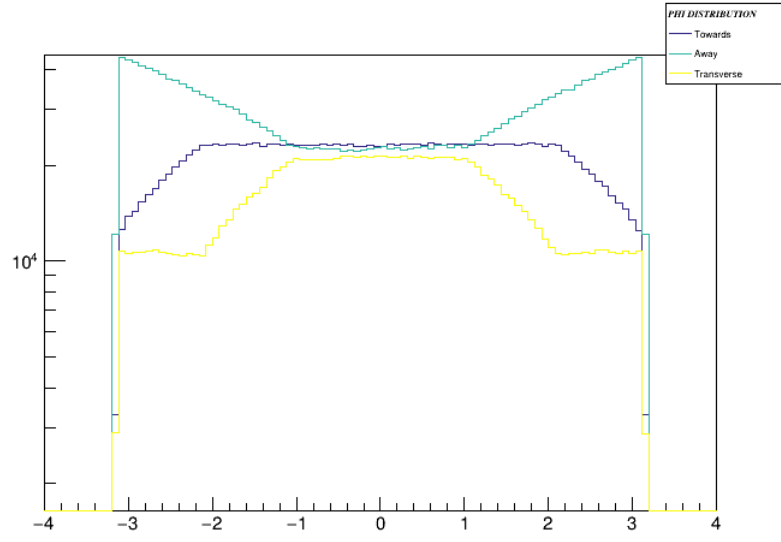


Fig 3(e):  $\phi$ -distribution with multiplicity class 80-100

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

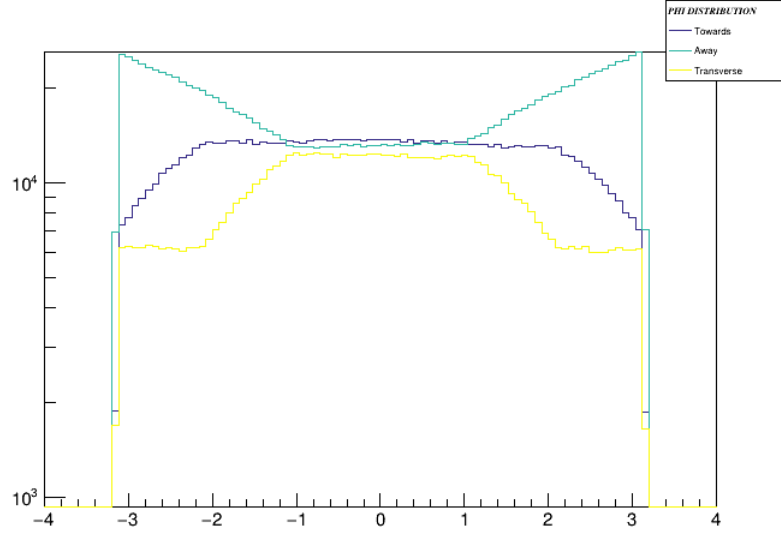


Fig 3(f):  $\phi$ -distribution with multiplicity class 100 onward

	Toward	Transverse	Away
<b>Entries</b>	969402	725731	1364341
<b>Mean</b>	-0.01801	-0.007086	0.01229
<b>Standard Deviation</b>	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.

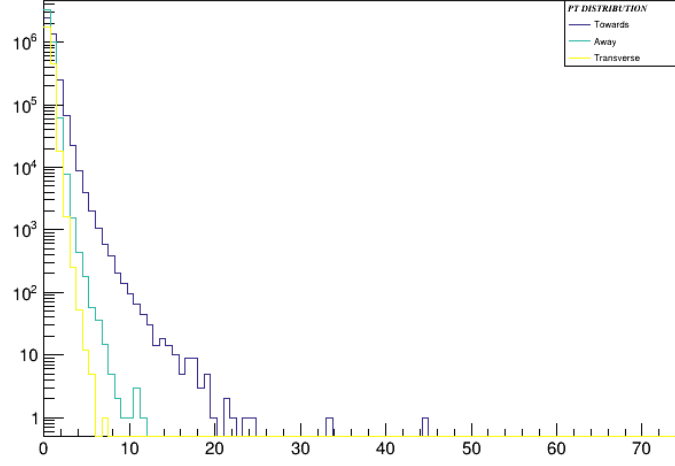


Fig 4(a): pT-distribution with multiplicity class 0-20

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

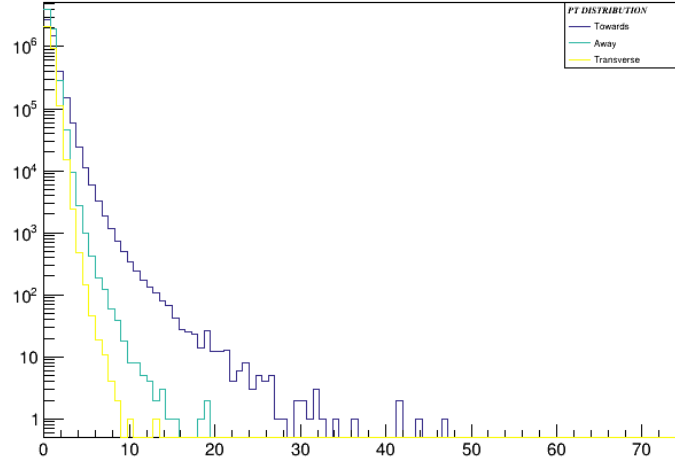


Fig 4(b): pT-distribution with multiplicity class 20-40

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

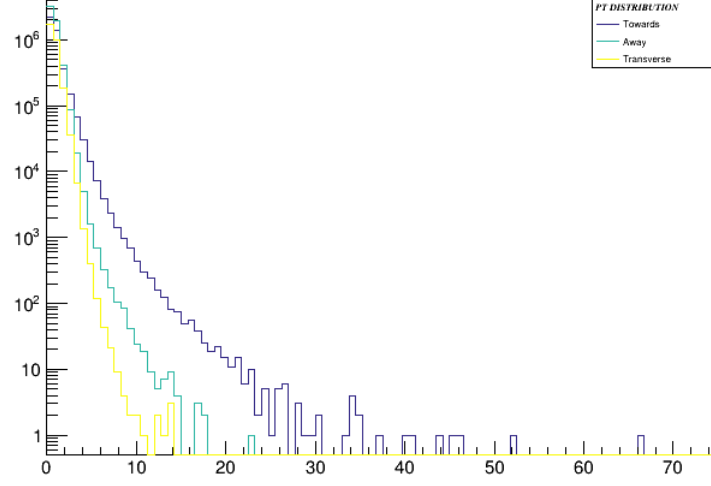


Fig 4(c): pT-distribution with multiplicity class 40-60

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

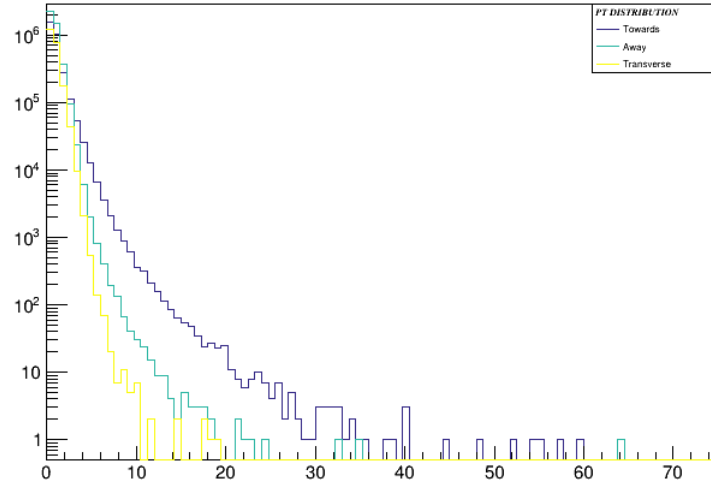


Fig 4(d): pT-distribution with multiplicity class 60-80

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

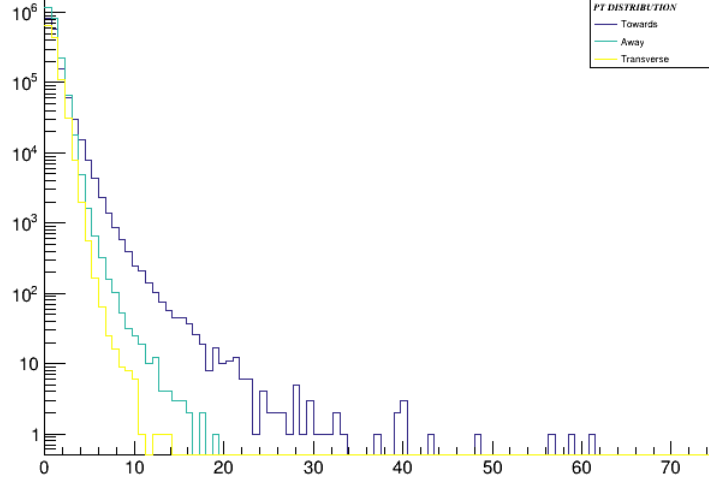


Fig 4(e): pT-distribution with multiplicity class 80-100

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

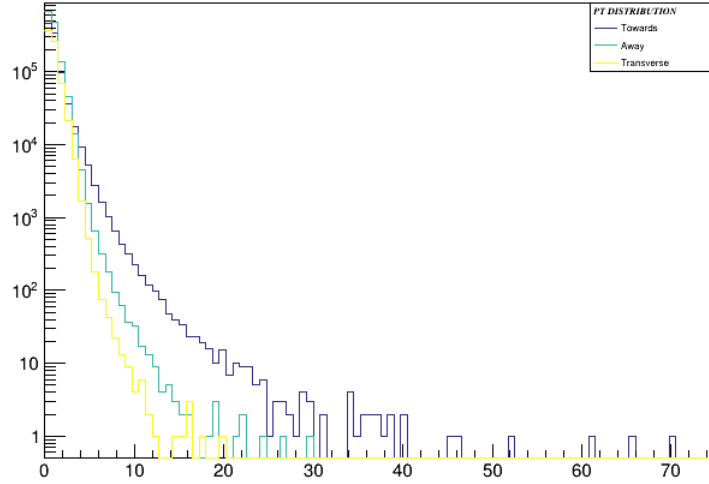


Fig 4(f): pT-distribution with multiplicity class 100 onwards

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

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

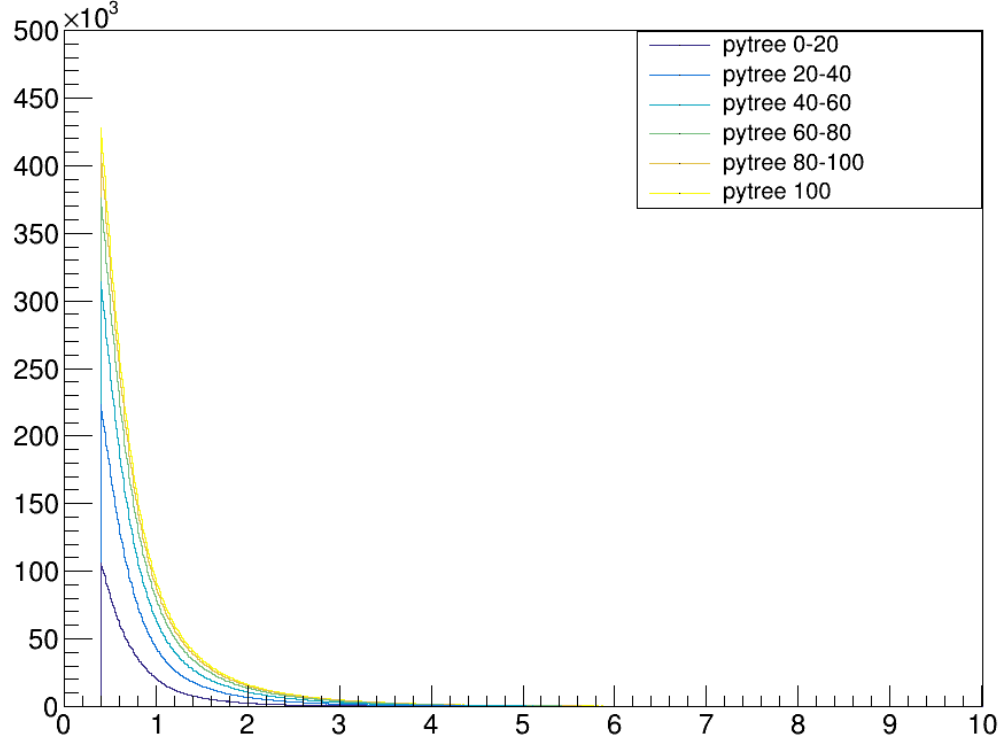


Fig 5(a): pT-distribution in towards region across all multiplicity classes

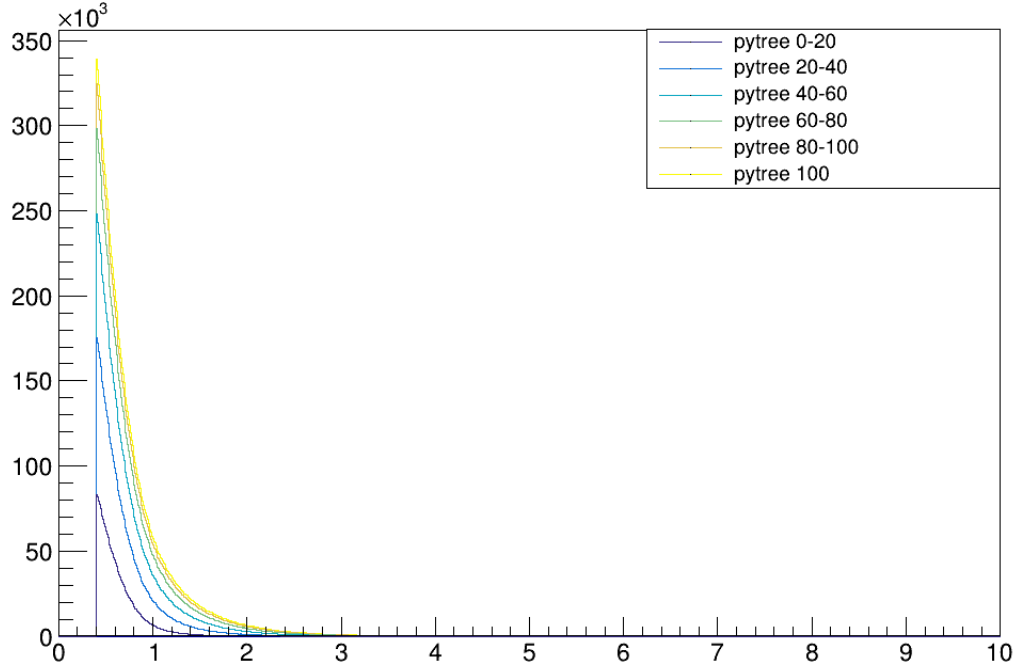


Fig 5(b): pT-distribution in transverse region across all multiplicity classes

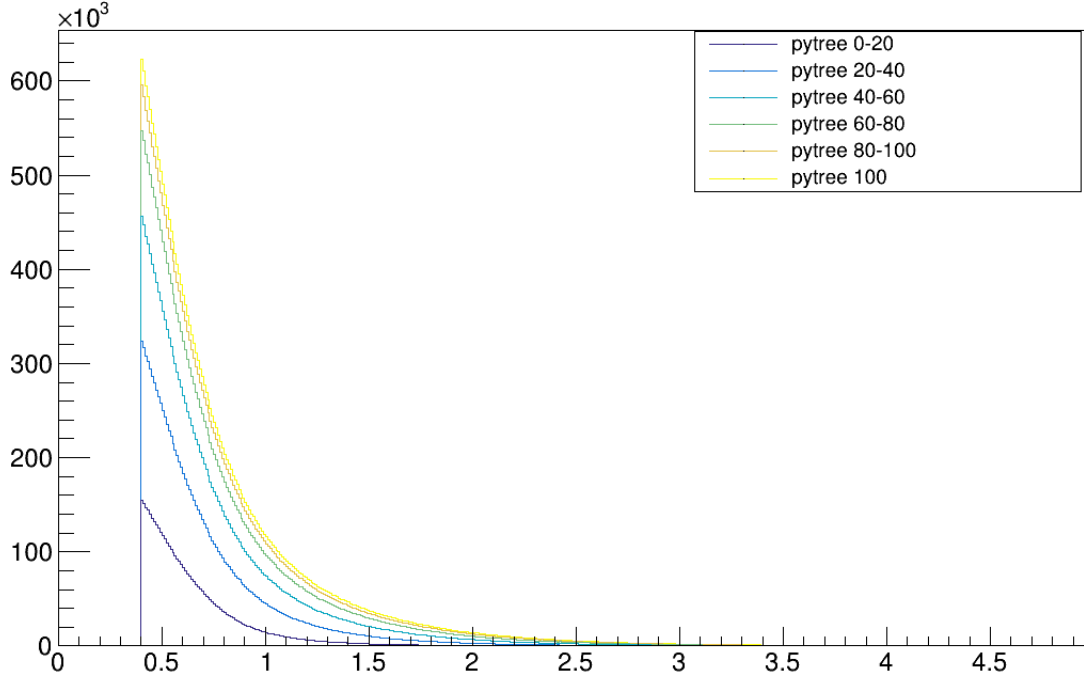


Fig 5(c): pT-distribution in away region across all multiplicity classes

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  $\sqrt{s} = 13\text{TeV}$ . 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](#)

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- [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)