

Multiplicity dependence of Forward Rapidity J/ ψ Production in Proton+Proton Collisions with ALICE at the LHC and Study of Particle Production in High-Energy Collisions

Ph.D. Thesis

By
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DISCIPLINE OF PHYSICS

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**Multiplicity dependence of Forward Rapidity
 J/ψ Production in Proton+Proton Collisions
with ALICE at the LHC and Study of Particle
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A THESIS

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DHANANJAYA THAKUR



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CANDIDATE'S DECLARATION

I hereby certify that the work which is being presented in the thesis entitled **"MULTIPLICITY DEPENDENCE FORWARD RAPIDITY J/ψ PRODUCTION IN PROTON+PROTON COLLISIONS WITH ALICE AT THE LHC AND STUDY OF PARTICLE PRODUCTION IN HIGH-ENERGY COLLISIONS"** in the partial fulfilment of the requirements for the award of the degree of **DOCTOR OF PHILOSOPHY** and submitted in the **DISCIPLINE OF PHYSICS, Indian Institute of Technology Indore**, is an authentic record of my own work carried out during the time period from July 2014 to July 2019 under the supervision of Prof. Raghunath Sahoo, Associate Professor, Discipline of Physics, Indian Institute of Technology Indore, Indore, M.P., India.

The matter presented in this thesis has not been submitted by me for the award of any other degree of this or any other institute.

Dhananjaya Thakur
(DHANANJAYA THAKUR)

This is to certify that the above statement made by the candidate is correct to the best of my knowledge.

Rahoo
(Prof. RAGHUNATH SAHOO)

Mr. **DHANANJAYA THAKUR** has successfully given his Ph.D. Oral Examination held on 27/8/19.....

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Dedicated to my village.....

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ABSTRACT

Quark-Gluon Plasma (QGP) is the deconfined state of strongly interacting matter, predicted by Quantum Chromodynamics (QCD), which is expected to exist in the early stages of evolution of the Universe, just after the Big-Bang. To access information about QGP; such as formation, evolution, composition etc., it is impossible to go back to the early stages of the Universe. A similar environment can be created in the laboratory by ultrarelativistic heavy-ion collisions, where a deconfined state of matter is expected to be formed at high temperature and/or energy density. Quarkonia, the bound state of heavy-quarks (*charm* or *bottom* quark) and its corresponding anti-quark, constitute one of the most interesting probes of the QGP because of its early formation in the collisions and therefore experience the whole QGP evolution. Besides this motivation, the study of quarkonium production is very interesting since it can contribute to our understanding of QCD, the theory of strong interaction. The study of production of *charmonia* ($c\bar{c}$) and *bottomonia* ($b\bar{b}$) in hadronic collisions is an important testing ground for QCD. From the discovery of J/ψ ($c\bar{c}$) meson in November 1974, till now, the understanding of its production mechanism is still an open problem to the scientific society. Although there are many theoretical models developed over the years, they are still not able to consistently reproduce the different physical observables such as the quarkonium production cross section, the transverse momentum distributions, and polarization within the same calculation framework. At the Large Hadron Collider (LHC), the study of event multiplicity dependent production of charmonium is a topic of high interest which is believed to give insight into the processes on the partonic level. In particular, it gives an opportunity to study the interplay between hard and soft mechanisms in particle production. Therefore, J/ψ production versus multiplicity measurement at the LHC energies is extremely interesting and represents a crucial step forward in understanding the physics involved in quarkonium production processes, and provides the necessary understanding for the measurements in search of QGP in heavy-ion collisions. No doubt, J/ψ is an unique candidate to probe the system formed in heavy-ion as well as pp collisions. But at the same time, one needs to understand the

nature of phase transition in heavy-ion collisions to have a complete picture of QCD. Solenoidal Tracker (STAR) at Relativistic heavy-ion Collider (RHIC) experiment has measured net-proton fluctuation in beam energy scan (BES) energies and a first order phase transition has been predicted with critical point around $\sqrt{s_{NN}} = 19.6$ GeV. As STAR operates at finite temperature and baryon chemical potential (μ_B), we expect a finite amount of baryon stopping at these energies. In that case, it is necessary to understand the signature of critical point explicitly by disentangling produced and stopped baryons. Lastly, to understand the system formed in heavy-ion (or pp) collisions, a proper understanding of the freeze out stages (hadronic phase) is highly needed. In such high multiplicity environments in heavy-ion and pp collisions, statistical model can be applied to study hadronic yield measurements and hence to draw the information about the freeze-out stages. It is believed that with local temperature fluctuations and long-range correlation, the system formed in heavy-ion and pp collisions may not acquire a thermal equilibrium. Therefore, a statistical model which describes the system away from thermal equilibrium, the Tsallis non-extensive statistics, is a suitable choice to infer the properties of freeze-out in such systems.

In this thesis, firstly, we study inclusive J/ψ production as a function of charged-particle multiplicity density in pp collisions at center-of-mass energies of $\sqrt{s} = 13$ TeV, obtained with the ALICE experiment at the LHC. This kind of study is complementary to that performed as a function of the collision centrality in heavy-ion collisions. Furthermore, the observation of long range, near-side angular correlations (ridge) in high-multiplicity pp collisions is an indication that pp collisions also exhibit collective (like) behavior as seen in heavy-ion collisions. The measurements of particle production as a function of the charged particle multiplicity in small systems provide a way to detect the possible presence of collective final state effects. The present analysis allows to search for these effects in events with a very high charged particle multiplicity. The study of J/ψ production with multiplicity is highly important to shed light in this context. For the current study, J/ψ mesons are measured at forward rapidity ($2.5 < y < 4$), via their decay into muon pairs ($\mu^+\mu^-$), which are

detected by the ALICE Muon Spectrometer. Whereas, charged-particle density has been estimated using Silicon Pixel Detector (SPD) at the mid rapidity ($|\eta| < 1.0$). In the second part of the thesis, we have discussed a technique to disentangle produced and stopped protons to have a clear understanding of the net-proton fluctuation result of STAR experiment. Finally, the freeze-out properties have been studied using Tsallis non-extensive statistics.

The structure of the thesis is organized as the follow:

- **Chapter 1** is a general introduction on quarkonia in high-energy physics: after a short reminder of QCD, we present an overview of the present status of knowledge on quarkonium hadroproduction mechanisms as explained by different theoretical models. Then, an elementary introduction to the physics of QGP is presented, pointing out the role of quarkonia as a probe of such deconfined state of partons. Finally, the study of role of Multipartonic interaction (MPI) in quarkonium production is introduced. The discussion is supported by some quarkonium experimental results and their comparison with theoretical models, where MPI is an important ingredient. In addition, a brief introduction to “baryon-stopping” and “Tsallis non-extensive statistics” has been presented.
- **Chapter 2** gives an overview of the ALICE experiment, with a detailed description of the Muon Spectrometer and its muon tracking and trigger system which is the detector used for the J/ψ measurements performed in this thesis.
- **Chapter 3** presents the work done in this thesis for the development of methods to measure the charged particle pseudorapidity density, $dN_{\text{ch}}/d\eta$ at the mid-rapidity. The improvements introduced in this thesis on the multiplicity computation for J/ψ studies, allow a better estimation of the multiplicity with a proper cross-check with different Monte Carlo (MC) models.
- **Chapter 4** is devoted to a detail description of J/ψ analysis in pp collisions which are carried out in this thesis. Followed by J/ψ yield extrac-

tion, the estimation of the J/ψ average transverse momentum ($\langle p_T \rangle$) in different multiplicity bins has been presented based on the study of the di-muon $\langle p_T \rangle$ invariant mass spectrum. This is done for the first time measured by ALICE in pp collisions.

- In **chapter 5** we have presented the work performed using pQCD inspire model, PYTHIA8, to understand the role of multipartonic interaction (MPI) in general and Color Reconnection (CR) in particular, to the multiplicity dependence study of J/ψ production. The study has been performed in different center-of-mass energies to know the energy dependence of MPI and CR to the multiplicity dependence of J/ψ production.
- **chapter 6:** In this chapter, we have presented the methodology and results obtained from phenomenological studies of “baryon-stopping” and “Tsallis non-extensive statistics” to extract information on the understanding of critical point and freeze-out properties of heavy-ion collisions.
- Finally, the conclusions drawn from the current studies have been presented in **chapter 7**.

PUBLICATIONS

List of Publications:

(Results from papers marked with [*] are included in this thesis.)

1. [*] **“Analysis Note: J/ψ production as function of charged-particle multiplicity in pp collisions at $\sqrt{s} = 13$ TeV at forward rapidity,”** *Dhananjaya Thakur* and Raghunath Sahoo, <https://alice-notes.web.cern.ch/node/734>, ANA-734
2. [*] **“Paper Draft: Forward rapidity J/ψ production as a function of charged-particle multiplicity in pp collisions at $\sqrt{s} = 5.02$ and 13 TeV with ALICE at the LHC,”** *Dhananjaya Thakur*, Anisa Khatun, Indranil Das, Tinku-Sinha Sarkar, Raghunath Sahoo, <https://alice-publications.web.cern.ch/node/5122>
(Paper is with IRC/PC in the ALICE Collaboration)
3. [*] **“Energy dependence of forward-rapidity J/ψ and $\psi(2S)$ production in pp collisions at the LHC”**
S. Acharya,....., *D. Thakur et al.* [ALICE Collaboration], Eur. Phys. J. C **77**, no. 6, 392 (2017)
4. [*] **“Quarkonium production as a function of charged particles multiplicity in pp and p-Pb collisions measured by ALICE at the LHC,”**
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5. [*] **“Indication of a differential freeze-out in proton-proton and heavy-Ion collisions at RHIC and LHC energies,”**
Dhananjaya Thakur, Sushanta Tripathy, Prakhar Garg, Raghunath Sahoo, Jean Cleymans, Adv.High Energy Phys. 2016 (2016) 4149352
6. [*] **“ Estimation of stopped protons at energies relevant for a beam energy scan at the BNL relativistic heavy-ion collider,”**
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D. Thakur, S De, R Sahoo, S Dansana, Phys.Rev. D 97 (2018), 094002

8. **“Multiplicity Dependence of J/ψ Production and QCD Dynamics in $p + p$ Collisions at $\sqrt{s} = 13$ TeV”**
S Deb, D Thakur, S De, R Sahoo arXiv:1808.01841, EPJ (Under Review)

9. **“ J/ψ production as a function of charged-particle pseudorapidity density in p -Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV”**
D. Adamova,.....,D. Thakur et al. [ALICE Collaboration], Phys. Lett. B 776, 91 (2018)

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CERN-EP-2019-125

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S. Acharya,.....,D. Thakur,.....,D. Thakur et al. [ALICE Collaboration], arXiv:1906.01371 [nucl-ex]
CERN-EP-2019-117

13. **“Scattering studies with low-energy kaon-proton femtoscopy in proton-proton collisions at the LHC”**
S. Acharya,.....,D. Thakur et al. [ALICE Collaboration], arXiv:1905.13470 [nucl-ex]
CERN-EP-2019-118

14. **“Inclusive J/ψ production at mid-rapidity in pp collisions at $\sqrt{s} = 5.02$ TeV”**
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CERN-EP-2019-096

16. **“Charged-particle production as a function of multiplicity and transverse sphericity in pp collisions at $\sqrt{s} = 5.02$ and 13 TeV”**
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CERN-EP-2019-094

17. **“Production of muons from heavy-flavour hadron decays in pp collisions at $\sqrt{s} = 5.02$ TeV”**
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[nucl-ex]
CERN-EP-2019-078

18. **“Measurement of charged jet cross section in pp collisions at $\sqrt{s} = 5.02$ TeV”**
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[nucl-ex]
CERN-EP-2019-070

19. **“Exploration of jet substructure using iterative declustering in pp and Pb-Pb collisions at LHC energies”**
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[nucl-ex]
CERN-EP-2019-087

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CERN-EP-2019-054

25. **“Measurement of $p\bar{\Lambda} \oplus \bar{p}\Lambda$ and $\Lambda\bar{\Lambda}$ interactions with femtoscopic correlations in Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV and $\sqrt{s_{NN}} = 5.02$ TeV”**
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26. **“Investigations of anisotropic flow using multi-particle azimuthal correlations in pp, p-Pb, Xe-Xe, and Pb-Pb collisions at the LHC”**

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34. **“Jet fragmentation transverse momentum measurements from di-hadron correlations in $\sqrt{s} = 7$ TeV pp and $\sqrt{s_{\text{NN}}} = 5.02$ TeV p-Pb collisions”**
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- S. Acharya,....,D. Thakur *et al.* [ALICE Collaboration], Phys. Rev. D **99**, no. 1, 012016 (2019)
40. **“Energy dependence of exclusive J/ψ photoproduction off protons in ultra-peripheral p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV”**
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42. **“Medium modification of the shape of small-radius jets in central Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV”**
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Chapter 1

Introduction

1.0.1 The Standard Model

The Universe is made up of some basic building blocks called fundamental particles, governed by four fundamental forces. The theory which encapsulates how these particles and three of the forces, namely the electromagnetic, weak and strong interactions are related to each other, is the Standard Model of particle physics¹. In more general, Standard Model is a quantum field theory based on the gauge symmetry $SU(3)_C \times SU(2)_L \times U(1)_Y$. Besides the masses of the elementary/fundamental particles, they are characterized by quantum numbers, such as the spin (S), electric charge (Q), baryon number (B), lepton number (L), color charge etc. The interactions between fundamental objects, quarks and gluons is described by strong force and they form hadrons such as pion, kaon, proton etc. Based on the spin of a particle, the elementary particles are classify into two classes, the fermions and the bosons. Quarks are fermions ($S=1/2$) having six varieties or flavors while gluons are massless bosons ($S=1$) with zero electric charge. A summary table with some of their properties is given in the Fig. 1.1. Unlike Quantum Electrodynamics (QED), the theory which describes the interactions between electrically charged particles, QCD is the theory describes the interactions between particles with color charges i.e *quarks* and *gluons* [1, 2]. Each quark can exist in one of three different color states, designed as *red*, *blue* and *green*. Gluons also carry a color charge and can therefore interact among each other (self-interaction). QED explains the interactions in term of exchange of massless bosons called *photons*, whereas QCD explains by the exchange of gluons. Similarly, the electroweak gauge

¹An introduction to standard model [3, 4]

bosons, $W^\pm$ and Z^0 bosons, are responsible for weak nuclear decays. The fourth fundamental interaction, the gravitation, is not included the standard model. The gauge boson for gravitational interaction is called *graviton*. The unified theory called the electroweak theory describes the electromagnetic and weak interactions [5–7]. The existence of a scalar particle, the Higgs boson (H), is triggered by the mechanism that breaks electroweak symmetry [8–10]. This mechanism is called as “Higgs mechanism” which leads to the generation of $W^\pm$ and Z^0 masses. Unlike the electric charge, the color charge doesn’t appear as a physical degree of freedom for systems at macroscopic scale. In our every day world, the quarks are confined into colorless states of hadrons through strong interaction [11, 12]. The hadrons are divided in to mesons, assembled in quark-anti-quark pairs ($q\bar{q}$), and baryons which assemble three quark states (qqq) together.

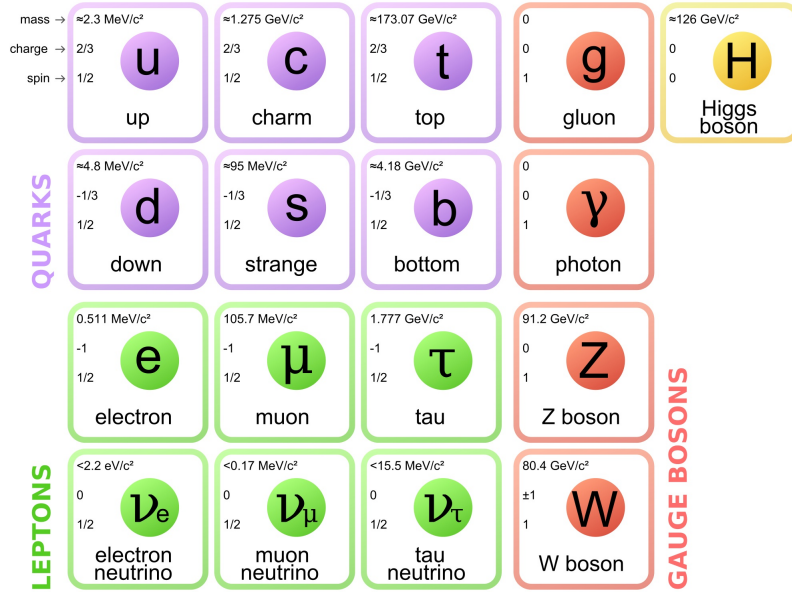


Figure 1.1. Elementary particles in the standard model with some of their properties [13]

1.0.2 Basics of Quantum ChromoDynamics

Quantum Chromodynamics (QCD) [14–17] is a Quantum Field Theory (QFT) which is responsible for the interactions of colored quarks and gluons. It results from the $SU(3)_C$ gauge symmetry, a Special Unitary group of dimension-3.

For the purposes of this thesis, it is sufficient to discuss the following essential properties of QCD:

QCD Lagrangian

QCD is the $SU(3)$ component of the $SU(3) \times SU(2) \times U(1)$ Standard Model of Particle Physics. The QCD Lagrangian is given by,

$$\mathcal{L} = \sum_q \bar{\Psi}_{q,a} (\gamma^\mu \partial_\mu \delta_{ab} - g_s \gamma^\mu t_{ab}^C A_\mu^C - m_q \delta_{ab}) \Psi_{q,b} - \frac{1}{4} F_{\mu\nu}^A F^{A\mu\nu}, \quad (1.1)$$

where the repeated indices are summed over. γ^μ represents Dirac γ -matrices. $\Psi_{q,b}$ represents the quark-field spinors of quark flavor q and mass m_q . Here “a” is the color index running from 1 to 3 (*i.e.* quarks come in three colors). A_μ^C correspond to the gluon fields with “C” running from 1 to 8 ($N_C^2 - 1 = 8$, eight kinds of gluons available in nature). The term t_{ab}^C is the generator of the $SU(3)$ group and are correspond to eight 3×3 matrices. The quantity g_s is the QCD coupling constant. The field tension $F_{\mu\nu}^A$ is defined as,

$$F_{\mu\nu}^A = \partial_\mu A_\nu^A - \partial_\nu A_\mu^A - g_s f_{ABC} A_\mu^B A_\nu^C \quad (1.2)$$

where f_{ABC} represent the structure constants of the $SU(3)$ group. The interaction terms of $\mathcal{L}_{QCD}$ allow quark-gluon and gluon-gluon interactions, and in particular the gluon self-interactions which is the key difference between QCD and QED. These interactions are responsible for special properties of QCD like asymptotic freedom and color confinement.

Asymptotic freedom

Asymptotic freedom is one of the most important and unique features of QCD, which states that the interaction strength between quarks and gluons become smaller when the distance between them become shorter or the energy density gets higher. Asymptotic freedom in the theory of the strong interaction has been discovered by David J. Gross and Frank Wilczek, and independently by

H. David Politzer [14–17]. The 2004 Nobel Prize in Physics was awarded jointly for the discovery of asymptotic freedom.

It can be understood by recalling electromagnetism. The electric force between two charges q_1 and q_2 separated by a distance, r in vacuum can be expressed by Coulomb's law as,

$$F = \frac{1}{4\pi} \frac{q_1 q_2}{r^2}. \quad (1.3)$$

Instead of vacuum, if the electric charges are present in a medium with dielectric constant ϵ , Eq. 1.3 can be modified as,

$$F = \frac{1}{4\pi\epsilon} \frac{q_1 q_2}{r^2}. \quad (1.4)$$

Therefore, the presence of dielectric medium introduces a screening effect and reduces the force between charges by an amount ϵ .

Similarly, in quantum field theory, the vacuum is not simply an empty space but it's the ground state of the system. It can be treated as a sea of continuously appearing and disappearing virtual particle-antiparticle pairs, called vacuum fluctuations, which are created out of the QFT vacuum. The field is weaker than would be expected in the case of a classical vacuum (completely empty). The phenomena, particle-antiparticle creation, is referred as vacuum polarization.

In QFT, due to the quantum fluctuations the vacuum becomes a polarizable medium. This implies that quark is not a quark alone, rather as it propagates, it can emit gluons which subsequently fragments into a $q\bar{q}$ pair and so on. Unlike QED photons, in QCD the color charged gluons can interact among themselves, so another way of vacuum polarization in QCD involving gluons turning into pairs of gluons.

As a result of vacuum property, the interaction between two electrons in vacuum modifies to,

$$F = \frac{e_{eff}^2}{4\pi r^2} = \frac{\alpha_{em}(r)}{r^2}. \quad (1.5)$$

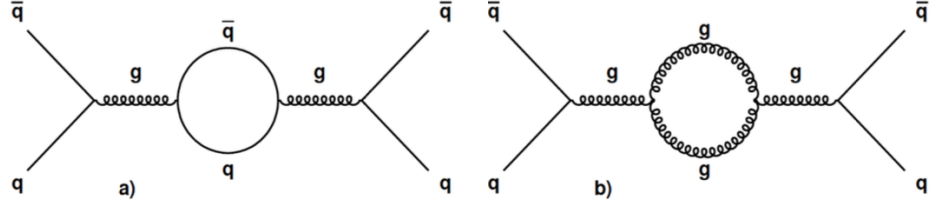


Figure 1.2. Vacuum polarization Feynmann diagrams affecting the interaction strength. a) The wavy line represents a photon (QED) or a gluon (QCD) makes the interaction weaker at large distances (screening effect). b) The non-linear interaction between gluons make the interaction weaker at short distances (anti-screening effect) [14, 17].

where e_{eff} and $\alpha_{em}(r)$ are the effective electron charge and electromagnetic running coupling constant. As $r \rightarrow 0$, the interaction strength gets stronger. Therefore, QED becomes a strongly-coupled theory at very short distance scale.

Similarly as QED, when the vacuum polarization applied in the case of QCD, the dependence of the strong coupling constant, α_s with the momentum transfer in the interaction (Q^2) can be written as [14–17]:

$$\alpha_s(Q^2) = \frac{4\pi}{(11 - \frac{2}{3}n_f)\ln\frac{Q^2}{\Lambda_{QCD}^2}} \quad (1.6)$$

where n_f is the number of quark flavors and the dimensional parameter Λ_{QCD} is technically identical to the energy scale Q , where $\alpha_s(Q^2)$ diverges to infinity, i.e $\alpha_s(Q^2) \rightarrow \infty$ for $Q^2 \rightarrow \Lambda_{QCD}^2$. In other word, Λ_{QCD} (≈ 200 MeV) is a constant which corresponds to the limit where, for smaller energy transfers, the perturbation theory is not applicable anymore to QCD calculations. Figure 1.3 shows the dependence given by Eq. 1.6 as well as a set of experimental measurements confirming its Q dependency.

The illustrative Fig. 1.3 shows the coupling constant α_s decreases at short distances (high energy), allowing quarks to behave as quasi-free particles. This phenomenon is called asymptotic freedom. On the other hand, at long distance (low energy), the strength of the coupling increases, which leads quarks to be confined in color neutral states. This property is called confinement. The world-average value of $\alpha_s(Q^2)$ measured by experiments at the energy scale

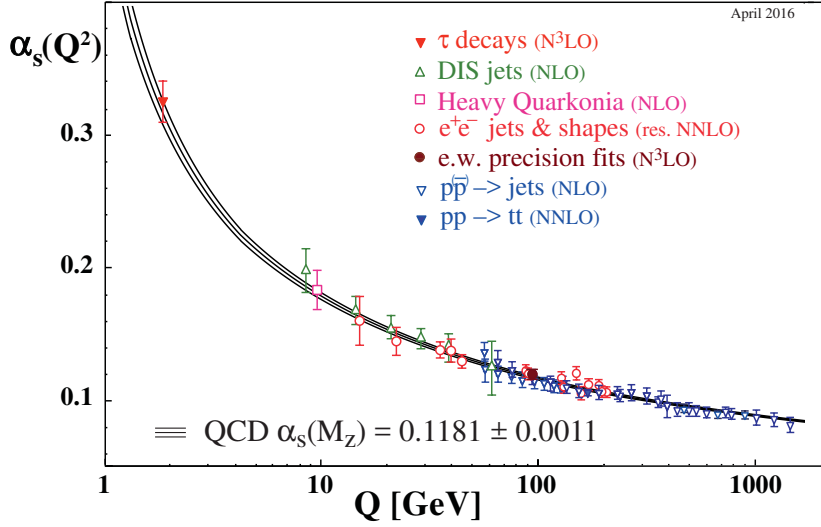


Figure 1.3. The running of the QCD coupling constant as a function of the momentum transfer (Q). Experimental data are compared to QCD predictions [18].

$$M_{Z_0} = 91.1876 \pm 0.0021 \text{ GeV is } \alpha_{s_{Z_0}} = 0.1184 \pm 0.0007.$$

Confinement

No free quarks and gluons are observed in Nature, i.e they are permanently confined into color-neutral hadrons. There is no analytic proof for quark confinement. The current theory says that confinement is due to the force-carrying gluons having color charge. For example, electromagnetic interaction in atom, as any two electrically charged particles separate, the electric fields between them diminish quickly, allowing electrons to become unbound from atomic nuclei. However, in case of strong interaction, as a quark-antiquark pair separates, the gluon field forms a narrow tube (or string) of color field between them. This is completely different from the behavior of electric field. When two quarks become separated, at some point it is more energetically favorable for a new quark-antiquark pair to spontaneously appear. An illustrative example is shown in Fig. 1.4 . If we try to break up a meson into quark, we have to put more and more energy into the system and at some point a new quark-antiquark pair is created out of the vacuum and we end up with two

mesons.

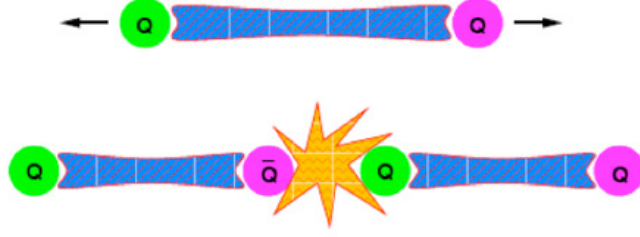


Figure 1.4. String breaking and quark-antiquark pair production [19].

As a result of this, when quarks are produced in particle accelerators, instead of seeing the individual quarks in detectors, we see "jets" of many color-neutral particles (mesons and baryons), clustered together. The confinement proof in QCD is a challenge that has not been met. Nevertheless, there have been some very interesting developments over the last years coming from lattice QCD investigations [20–22].

Chiral symmetry breaking

Chiral symmetry is a symmetry of the Lagrangian which allows independent transformation of the left-handed and right-handed components of the fermions. Where, "handedness" can be understood from the concept of helicity. The term "handedness" is assigned to a particle depending on whether the projection of the spin of the particle points in or opposite to the direction of motion, as shown in Fig.1.5.



Figure 1.5. Example of right-handed and left-handed helicity [23].

Let us consider the fermionic part of the QCD Lagrangian with the two

lightest quarks [24] ,

$$\mathcal{L} = \bar{u}i\not{D}u + \bar{d}i\not{D}d - m_u\bar{u}u - m_d\bar{d}d. \quad (1.7)$$

If we ignore the current quark masses, then the Lagrangian in Eq. 1.7 has $SU_V(2)$ isospin symmetry. In terms of the left-handed and right-handed components of the quark doublet Q , the Lagrangian can be written as

$$\mathcal{L} = \bar{Q}_L i\not{D}Q_L + \bar{Q}_R i\not{D}Q_R, \quad (1.8)$$

where the Q_L and Q_R are given by

$$Q_L = \left(\frac{1 - \gamma^5}{2}\right) Q \quad \text{and} \quad Q_R = \left(\frac{1 + \gamma^5}{2}\right) Q \quad (1.9)$$

The Lagrangian in Eq.(1.8) is symmetric under separate unitary transformations of $SU_A(2)$. Thus for massless Fermions, Dirac Lagrangian is invariant under the transformation, $SU_V(2) \times SU_A(2)$, i.e. vector and axial vector currents are conserved. This symmetry is called Chiral symmetry. A mass term like $m\bar{Q}Q$ in the Lagrangian explicitly breaks the chiral symmetry as it mixes the left-handed and the right-handed quarks,

$$m\bar{Q}Q = m\bar{Q}_L Q_R + m\bar{Q}_R Q_L. \quad (1.10)$$

As u and d quarks have very tiny mass, the QCD Lagrangian approximately respects the chiral symmetry. Chiral symmetry is spontaneously broken in the QCD vacuum with a non-zero vacuum expectation value of $\bar{Q}Q$. If we consider three lightest quarks, the Nambu-Goldstone (NG) bosons associated with the dynamical breaking of the flavor-SU(3) chiral symmetry are pions, kaons and η -meson [25], which are not massless because of the finite but small masses of the light quarks.

Nature of QCD phase transition

Figure 1.6 shows the current understanding about nature of confinement-deconfinement phase transition, in a baryon free matter, as a function of quark mass m_u, m_d and m_s . Following are the predictions,

- The phase transition is 1st order for pure gauge theory ($m_q \rightarrow \infty$).
- For $m_q \rightarrow 0$, the Lagrangian is chirally symmetric and there is a chiral symmetry restoration phase transition. It is also a 1st order phase transition.
- For $0 < m_q < \infty$, there is neither confinement-deconfinement phase transition nor a chiral symmetry restoring phase transition. The system undergoes a cross-over transition.

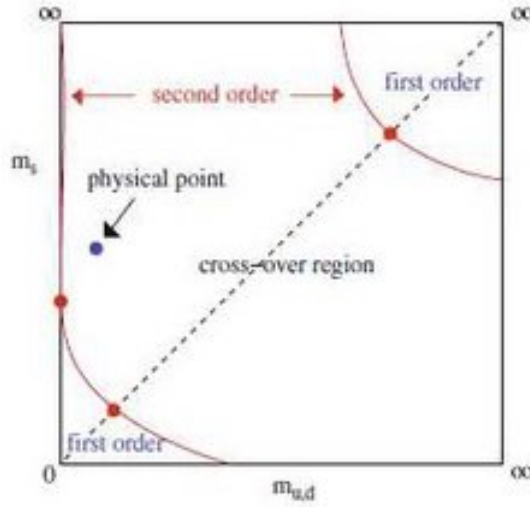


Figure 1.6. Phase transition as a function of quark mass m_u, m_d and m_s [24].

From theoretical considerations, 1st order QCD phase transition is expected in baryon rich matter. Since at $m_q \approx 0$ deconfinement transition is a cross-over, one expects a QCD critical end point where the 1st order transition line ends up and the cross-over starts. Location of the QCD critical end point is of current interest.

1.0.3 QCD phase diagram and Quark-Gluon Plasma

At a very high temperature and/or high baryon chemical potential, the strength of the strong force becomes weak, and hence the quarks and gluons become deconfined. The deconfined state of matter is called Quark-Gluon Plasma (QGP). This is due to the properties of asymptotic freedom. QGP is believed to exist few micro-seconds after the Big-Bang, and at the core of the Neutron stars. The phase diagram of strongly interacting matter is shown in Fig. 1.7 as a function of temperature and net baryon density. Quarks and gluons are confined into hadrons at low temperature and low density. At low temperatures and high densities, the matter can be described as a degenerated gas of neutrons, which is believed to exist in the neutron stars [26]. For low temperatures and very large baryochemical potential (μ_B), the quarks begin to form color Cooper pairs. Therefore, a color superconductor state is believed to exist [27].

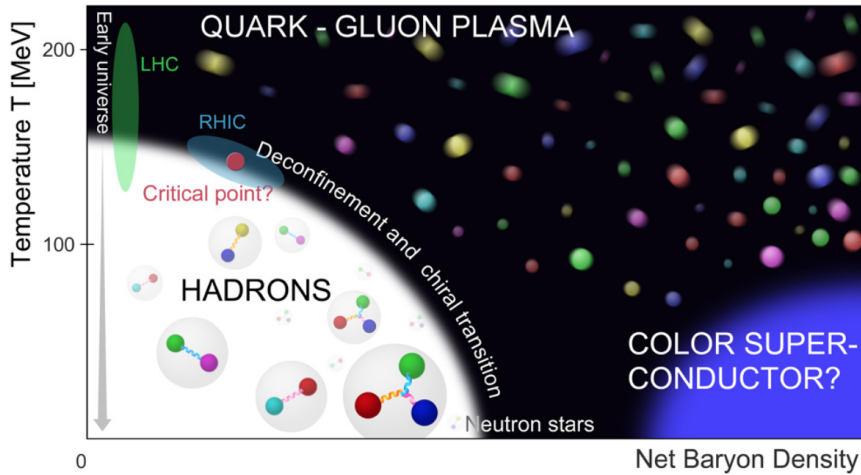


Figure 1.7. The schematic of a QCD phase diagram [30].

Lattice QCD at finite temperature allows to study the QCD equation of state, which can be used to characterize the transition of a hadronic matter to QGP. The results from Lattice QCD calculations at $\mu_B = 0$ show that the deconfinement transition occurs at a critical temperature $180 \leq T_c \leq 200$ MeV [28]. The corresponding critical energy density has been determined to be about $1 \text{ GeV}/\text{fm}^3$ [29]. Lattice QCD results have shown that at small or vanishing values of μ_B the deconfinement transition is not a phase transition

but a continuous cross-over due to the non-zero mass of the u, d and s quarks. Besides the study of QCD phase diagram by lattice QCD, its experimental validation is highly necessary.

1.0.4 QGP in Heavy-Ion collisions

The experimental quest for Quark Gluon Plasma has been going on for more than 30 years by now. It is proposed that QGP could have been produced in high-energy collisions of heavy nuclei. The main reason of colliding large nuclei is that, in order to obtain a proper deconfinement, the region of space where high energy density is achieved should be much larger than a typical hadron size. The evolution of such a system is very complicated. The system formed in heavy-ion collisions and its evolution, can be studied by the Bjorken scenario [31] .

Evolution of a heavy-ion collision: Relativistic Hydrodynamics

Bjorken gave a picture of the space-time evolution of a heavy-ion collision. The evolution of the formed system is treated with the Landau hydrodynamical model [32]. Bjorken took the following assumptions:

- The nuclei crossing time is smaller than the characteristic time of the strong interaction. The crossing time can be estimated as $\tau_{cross} = 2R/\gamma$, where R is the nuclear radius and γ is the Lorentz factor. The condition $\tau_{cross} \ll \tau_{strong}$ is satisfied for $\gamma > 12$, which is achieved for center-of-mass energies per nucleon above $\sqrt{s_{NN}} > 25$ GeV.
- The mid-rapidity plateau of the particle production distribution and rapidity symmetry of the system lead to simple solutions of the hydrodynamic equations.

In Fig. 1.8, the different stages of the space-time evolution of the collision described by the Bjorken scenario are shown. Different stages of heavy-ion collisions, QGP formation and transition to ordinary matter are described.

The system can be treated as expanding hadronic gas, when all the quarks and gluons are again confined.

– **Freeze-out:**

Hadronic matter will also be in thermal equilibrium. Constituent hadrons will collide to maintain local equilibrium. This stage is divided into two parts:

- * ***Chemical freeze-out (CFO)*** The relative abundances of hadrons is fixed when the inelastic collisions between hadrons stop. Hadron abundances will remain fixed during the system evolution after the CFO. However, due to elastic collisions, local equilibrium can still be maintained and system cools and expand with fixed hadron abundances.
- * ***Kinetic freeze-out (KFO)*** Eventually a stage comes when average distance between the constituents will be larger than the system size. The hadrons do not interact elastically anymore and stream freely to the detectors.

A variety of experimental data from heavy-ion collision experiments, are successfully explained in ideal hydrodynamical models [34, 35]. Some problems however remained. For example, ideal hydrodynamics description of experimental data becomes poorer as the collisions become more and more peripheral. The life-time of the QGP is so short that it is not possible to have direct experimental observation. In the next section, we have discussed the summary of major experimental probes for QGP.

Summary of signatures of QGP

We expect that QGP is produced in ultra-relativistic heavy-ion collisions. QGP, even if produced in a collision, is a transient state, it expands, cools and hadronises. Any information about the QGP phase, if produced in high energy nuclear collisions, has to be obtained from the observed final state hadrons.

- **The global observables:**

The global observables provide information regarding the initial energy density and geometrical aspects of the collision. The initial energy density can be estimated through the measurement of the transverse energy (E_T) and charged particle multiplicity ($dN_{ch}/d\eta$) [31, 34]. Also, using charged-particle multiplicity one can draw geometrical information like impact parameter, number of participating nucleons and number of binary nucleon-nucleon collisions [36]. Statical model can be applied on hadronic yield measurements to obtain the system temperature and baryochemical potential at chemical freeze-out [37]. There is a large variety of probes, but here we just give a general idea and mention a few of them.

- **The early stage signatures:**

These are the signatures which are produced early in the collision and hence their production is not affected by rescattering or system expansion. They are the very good probes, which can give information of perturbative QCD processes and about the formation of QGP. Among these probes, some are: electroweak bosons (γ), di-lepton, $W^\pm$, Z^0 , high- p_T hadrons, particle containing heavy flavour quarks (e.g J/ψ , Υ , D-meson etc.) [38–41]. Thermal photons are directly emitted from the QGP and they do not interact strongly and hence can be used to extract information about the initial temperature of the system [42, 43]. $W^\pm$, Z^0 do not interact strongly and are used to study parton distribution functions (PDF). Also, the energy loss suffered by hard-scattered partons passing through the QGP modify the yields w.r.t the yield without medium (minimum-bias pp collisions). To study this medium modification, a observable called R_{AA} is defined for AA collisions, considering the minimum-bias pp collisions as base line measurement. $R_{AA} < 1$ hints for modification of the medium. Heavy flavor quark pairs such as $c\bar{c}$ (or $b\bar{b}$) pairs, which has large mass can only be created in the primary nucleon-nucleon collisions and hence can be considered as one of the best probe to study and characterize a possible QGP medium, as it experiences the evolution of whole system. The relative yields of mesons with hidden ($c\bar{c}$ bound states are called charmonium) and open charm ($c\bar{q}$ and $q\bar{c}$) can change in a decon-

finer medium as compared to a hadron medium. Charmonium states are formed during the QGP phase, so their production rates can be used as a probe of QGP formation.

- **Strangeness enhancement**

An enhancement of strangeness production in A-A collisions relative to p-p or p-A collisions has been suggested as a potential probe for QGP formation [44]. However, recent measurements by ALICE, have observed strangeness enhancement for p-p collisions at $\sqrt{s} = 7$ TeV [45] as well. Therefore, it has become a topic of debate within scientific community. For the completeness, we discuss in brief on strangeness enhancement and its importance in this section.

It has been speculated that the yields of strange and multi-strange hadrons should get enhanced in the presence of QGP. This can be understood as follows. The rate of production of strangeness is described by Schwinger factor, as long as there is no chemical-equilibrium [44]. This factor depends on mass as Ae^{-km_q} . Where m_q is mass of quark. A and k are constant parameters. So the production of heavier quarks like the strange quark is strongly suppressed compared to that of light quarks. Contrary to it, if the system reaches chemical equilibrium, the yield of different quarks and anti-quarks are almost same. This is due to the fact that the QGP-phase exists long enough in chemical-equilibrium to establish u,d,s quarks reach a similar ratio. If no QGP is produced, the chemical equilibrium of the hadronic phase has a much lower strangeness content. Therefore, one can distinguish the production of a hadronic phase from the QGP phase by looking at the strangeness of the produced particles. In a QGP phase usually strangeness is enhanced because of the following mechanism: $gg \rightarrow s\bar{s}$, $q\bar{q} \rightarrow s\bar{s}$.

- **Jet quenching**

In Fig. 1.9, di-hadron correlations in the azimuthal plane, in p+p, d+Au and Au+Au collisions are shown. A high p_T trigger particle is fixed and $\Delta\phi = \phi_{associated} - \phi_{trigger}$, the difference of azimuthal angle between the

trigger and associated particles, is calculated. The peak at $\Delta\phi = 0$, is called near side peak (near to trigger particle) and peak at $\Delta\phi = \pi$, is called away side peak (away from trigger particle). The double peak structure in p+p and d+Au collisions can be understood in terms of two jet events. However, in Au+Au collisions, the away side peak is strongly suppressed. Strong suppression of the away side peak is the experimental evidence of jet quenching [46]. This is explained as follow: if a di-jet is produced near the surface the medium (QGP), one of the jets escapes into the vacuum and fragments. The other enters the medium and loses its energy in the medium before fragmentation.

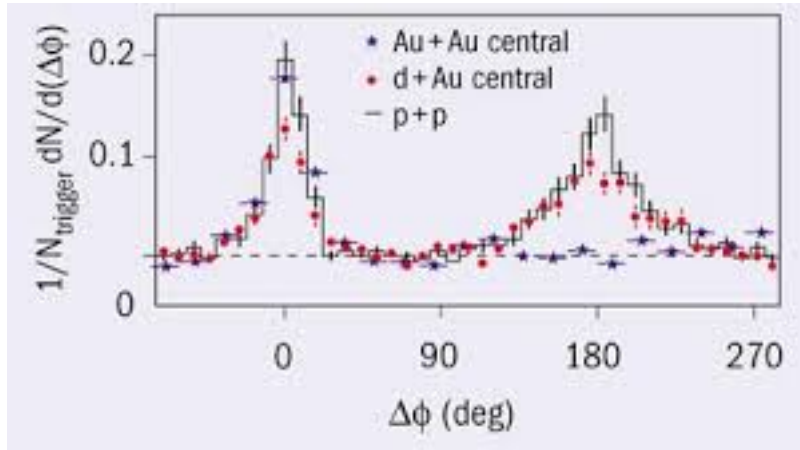


Figure 1.9. Two particle correlation in the azimuthal plane for the center-of-mass energy of 200 GeV for Au-Au, d-Au and p-p collisions [47].

- **Collective flow**

The azimuthal distribution of produced particles is one of the important observables of QGP. In Fig.1.10, geometry of a collision at non-zero impact parameter collision is shown. The overlap region of the two nuclei is the participant region, where most of the collisions occur. The participants in coordinate space do not possess azimuthal symmetry. Multiple collisions among the constituent particles translate this spatial anisotropy into momentum anisotropy of the produced particles. The observed momentum anisotropy is called collective flow and has a natural explanation in a hydrodynamic model [48, 49] .

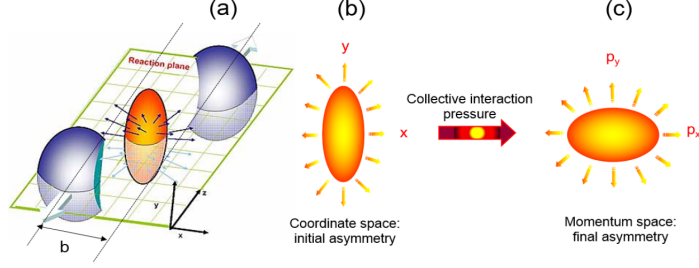


Figure 1.10. Schematic picture of a non-zero impact parameter collision [50].

1.1 Heavy quarkonium production in high-energy pp collisions

Heavy-flavor hadrons, containing open or hidden charm and beauty flavor, are among the most important tools for the study of Quantum Chromodynamics (QCD) in high-energy hadronic collisions [38]. The production mechanisms in pp collisions and their modification in proton-nucleus collisions (p-A) to the investigation of the properties of the hot and dense strongly interacting QGP in nucleus-nucleus collisions (AA), heavy-flavors are very useful probes. Heavy-flavor production in pp collisions provides important tests of our understanding of various aspects of QCD. Like positronium (e^+e^- system), the hadron containing charm and anti-charm quark, is named as charmonium. Charmonium is discovered in November 1974. The heavier sibling of charmonium containing bottom and anti-bottom quark is called bottomonium. As like hydrogen atom allows to explain the atomic physics, charmonia play an important role for understanding hadronic dynamics. Secondly, charmonia involves both perturbative and non-perturbative aspects of QCD. The production of the heavy-quark pair, $Q\bar{Q}$, is expected to be perturbative since it involves momentum transfers at least as large as the mass of the considered heavy quark. On the other side, the evolution of the $Q\bar{Q}$ pair into the physical quarkonium state is non-perturbative. Charmonium spectroscopy is briefly discussed in section 1.1.1. Section 1.1.2 is devoted to the discussion on charmonium production mechanisms.

1.1.1 Charmonium Spectroscopy

The charmonium family can be described (partially) by a non-relativistic description [51]. The mass difference ΔM between the charmonium ground state (J/ψ) and its first radial excitation (ψ) with respect to either of the masses provides an estimate of the relativistic parameter.

$$\frac{v^2}{c^2} \sim \frac{\Delta M}{M} \sim 0.2. \quad (1.11)$$

Such moderate (not very small magnitude) of the relativistic effects, allows to treat the charmonium dynamics in the non-relativistic limit including the relativistic effects as perturbations in powers of v/c . In non-relativistic picture, analogous to the spectroscopy of the hydrogen atom, different quantum states of the $c\bar{c}$ system can be characterized by the quantum numbers “L” (the orbital angular momentum), “S” (spin), “J” (total angular momentum) and the principal quantum number “n”. The spectroscopic notation of charmonium state is given as,

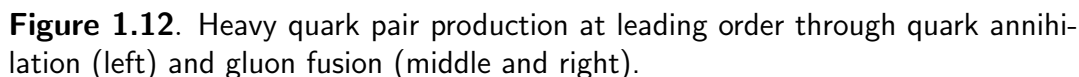
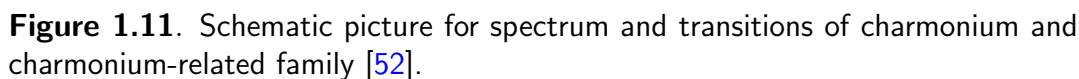
$$n^{2S+1}L_J, \quad (1.12)$$

where $2S + 1$ represents spin multiplicity. The lower state represents $n=1$, $S=0$, $L=0$ (S), hence $J=0$, with the notation $1S_0^1$ (η_c resonance). The “L” value determines the parity (P) for each of the states: $P = (-1)^{L+1}$, while “L” and “S” together gives charge-conjugation parity: $C = (-1)^{L+S}$. The schematic diagram of the spectrum of the known charmonium and charmonium-related states and their transitions, is presented in Fig. 1.11.

1.1.2 Theoretical Models for Charmonium Production

A $Q\bar{Q}$ pair can be created in 8 color states with a net color charge (color-octet state) and 1 state without color charge (color-singlet). For the creation of physical resonance, charge of the pair should be neutralized. It can be achieved through interaction with the surrounding color fields.

In this section, we present various theoretical models describing the direct



The creation of the $c\bar{c}$ pair, in the initial partonic interaction, and the successive hadronization into a charmonium resonance are governed by the following parton-parton cross section [53]:

19

- $\hat{s}$ is the squared of center-of-mass energy of the partonic interaction.
- $^{2S+1}L_J^c$ represents the quantum state of $c\bar{c}$ pair.
- “X” indicates the other product might be created in the initial partonic interaction.
- ψ is the generic charmonium resonance with mass M_ψ produced.
- Q^2 is the transfer momentum of the reaction.

A quarkonium state ($Q\bar{Q}$) has mainly three intrinsic momentum scale, such as: the heavy quark mass (m_Q), the momentum of heavy quark in the quarkonium rest frame ($m_Q v$) and binding energy of Q and $\bar{Q}$ (of the order $\sim m_Q v^2$). The quantity “ v ” indicates the typical velocity of the heavy quark in the quarkonium rest frame.

As discussed in the previous section, the production of $Q\bar{Q}$ pair happens at a scale $Q^2 \gg \Lambda_{QCD}^2$ [54, 55]. It is treated as a perturbative process and involves short distances (or time scale of the order $1/Q$). On the other hand, the evolution of $Q\bar{Q}$ pair into quarkonium state would involve smaller dynamic scales ($\sim \Lambda_{QCD}$) and large distance (or time scale of the order $1/\Lambda_{QCD}$) is a non-perturbative process. This allows to re-express the parton-parton cross section, shown in Eq. 1.15 as [53],

$$\begin{aligned} \hat{\sigma}(a+b \rightarrow \psi + X \rightarrow \psi; \hat{s}, m_c^2, Q^2, \alpha_s(Q^2)) &= \hat{\sigma}_{pQCD}(a+b \rightarrow c\bar{c} (^{2S+1}L_J^c) + X; \\ &\hat{s}, m_c^2, Q^2, \alpha_s(Q^2)) \times \hat{\sigma}_{npQCD}(c\bar{c} (^{2S+1}L_J^c) \rightarrow \psi). \end{aligned} \quad (1.14)$$

This property of QCD allows to calculate $\hat{\sigma}_{npQCD}$ as a perturbative expansion in the powers of $\alpha_s(Q^2)$ using pQCD approach. The final result is then obtained at a certain order as; leading order (LO): $\hat{\sigma}_{pQCD} = \hat{\sigma}_i \cdot \sigma_s^i$, next to leading order (NLO): $\hat{\sigma}_{pQCD} = \hat{\sigma}_i \cdot \sigma_s^i + \hat{\sigma}_{i+1} \cdot \sigma_s^{i+1}$, and so on. The $\hat{\sigma}_{npQCD}$ is parametrized using phenomenological models.

Nearly, all the quarkonia production models discussed nowadays, the idea of a factorization between the pair production and its binding is introduced.

Mainly, differ essentially in the treatment of the hadronisation, although some may also introduce new ingredients in the description of the heavy-quark-pair production. In the following, we briefly describe three of them which can be distinguished in their treatment of the non-perturbative part.

The Colour-Evaporation Model (CEM)

The production cross section of quarkonia is expected to be directly connected to that to produce a $Q\bar{Q}$ pair in an invariant-mass region where its hadronisation into a quarkonium is possible, i.e in between the kinematic threshold of quarkonium ($2m_Q$) and open-heavy flavor ($2m_H$). The cross section to produce a given quarkonium state is supposed to be obtained after a multiplication by a phenomenological factor which is related to the probability that the pair eventually hadronises into this state (F_Q). This factor is determined experimentally. Mathematically;

$$\sigma_Q = F_Q \int_{2m_Q}^{2m_H} \frac{d\sigma_{Q\bar{Q}}}{dm_{Q\bar{Q}}} dm_{Q\bar{Q}} \quad (1.15)$$

This calculation can be done at Leading Order (LO) (at α_s^3) in perturbation theory or at Next-to Leading Order (NLO) (at α_s^4) to account for the p_T dependence. This model [56] has several discrepancies. Like, it is unable to give predictions of the quarkonium polarization and that also some discrepancies are found in the description of p_T spectra.

The Color-Singlet Model (CSM)

In this model, the production of the bound state is completely correlated to the $Q\bar{Q}$ production [57–60]. In this way, the heavy quark pair has to be produced in a color-singlet state with the same quantum numbers as the charmonium. The non-perturbative factor of the quarkonium cross section is proportional to the bound state wave function or its derivative, which can be extracted from data. As an example, the CSM successfully describes the J/ψ and Υ ($b\bar{b}$) total

cross sections as a function of the collision center-of-mass energy [60]. However, it fails on the predictions of $\psi(2S)$ data.

The Color-Octet Model (COM)

The COM [61] based on Non-Relativistic Quantum ChromoDynamics (NRQCD) [62]. In addition to the usual expansion in powers of α_s , NRQCD further introduces an expansion in v . The factorization for COM uses NRQCD to separate the short-distance factors, which account for $Q\bar{Q}$ creation, from the long-distance matrix elements, which account for the transition to a physical bound state. The COM calculations require an infinite sum of terms running over all possible quantum numbers of the heavy quark pair. In each term, the short distance coefficients are the perturbatively calculated (expansion in α_s) production rates of the heavy quark pair in the corresponding state n (color, spin and angular momentum), and the long-distance matrix elements are the NRQCD matrix elements that give the probability of a heavy quark pair in the state n to form the bound state. The transition of the intermediate $c\bar{c}$ state into a physical J/ψ occurs through the emission of soft (non-perturbative) gluons, described by the long-distance matrix elements. The long-distance matrix elements can be determined from cross-sections fits in data. COM has successfully described many observables. But, a full proof of factorization does not yet exist. It had problems in describing polarisation results of J/ψ for pp collisions at Tevatron.

1.1.3 Underlying event and Multiple Parton

Interactions in hadronic collisions

The understanding of event structure in hadronic collisions is a very challenging task. It is said that the physics associated with it is sub-divided into a number of components, like hard central interactions, fragmentation of beam remnant, multi-partonic interactions (MPI), and initial and final state radiation (ISR and FSR) etc. Technically, this is called as underlying event (UE), which is the sum of all the processes that build up the final hadronic state in a collision. The UE

activity at a given centre-of-mass energy is expected to increase with the hard scale in the interaction. Harder scale of events correspond to smaller impact parameter. Events with a harder scale are indeed expected to correspond to interactions with a smaller impact parameter, which in turn should enhance MPI and hence multiplicity [63]. This increased activity is observed to reach a plateau for high scales, corresponding to an MPI saturation effect for impact parameters selected by a sufficiently hard leading interaction. Conversely, for events with the same hard scale (multiplicity) but taken at different values of the centre-of-mass energy, MPI activity is expected to increase with $\sqrt{s}$ [63]. The present analysis is focused on measurements that can contribute to the understanding of the UE dynamics with different hard scales and $\sqrt{s}$. On top of that, color reconnection (CR) is a microscopic mechanism that describes the interactions that can occur between color fields during the hadronization transition. It is a key ingredient which is needed to explain the increase of the average transverse momentum as a function of charged-particle multiplicity and the multiplicity-dependent event shape studies [64]. The importance of the UE relies on the fact that it can shed light in the search for new physics phenomena at hadron colliders or even in the quest for precise Standard Model measurements.

Role of MPI in J/ψ production

To look at exclusive final states and not only inclusive ones, it is needed to have a full description of hard processes in a complete event. It is necessary to understand the description of the interplay between the hard and the soft components of the event as well as of color flow and energy conservation is mandatory. The NA27 has experiment performed a study that relates open charm production and underlying event properties for pp collisions at $\sqrt{s} = 27$ GeV. It was found that charged-particle multiplicity distribution in events with and without charm production differs by 20% [65], indicating already a different behavior in multiplicity distribution. The Fig. 1.13 shows the distribution of relative charged-particle multiplicity for pp collisions at $\sqrt{s} = 7$ TeV. It can be shown from the figure that the charged particle produced in highest multiplicity

is around 5.5 times that of minimum bias.

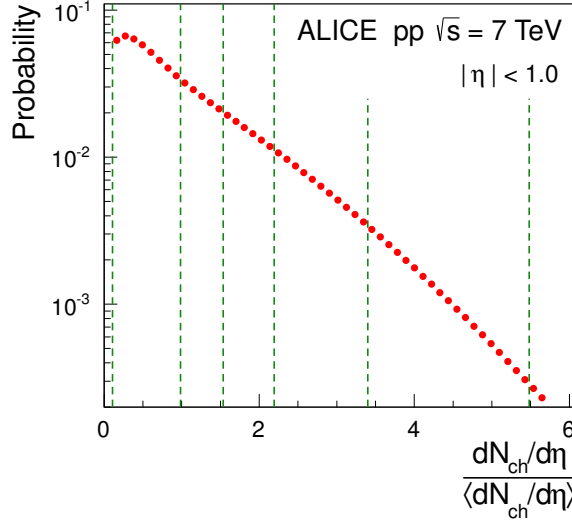


Figure 1.13. The distribution of the relative charged particle density ($\frac{dN_{ch}/d\eta}{\langle dN_{ch}/d\eta \rangle}$) reconstructed around mid-rapidity ($|\eta| < 1.0$) after correction for SPD inefficiencies [65].

The measured charged particle multiplicity values in pp collisions is higher than in peripheral Cu-Cu at RHIC at $\sqrt{s_{NN}} = 200$ GeV [66]. With such high energy density reach in pp collisions at the LHC, some model predict the collective behavior in high multiplicity pp collisions. Therefore, there is a chance of the possibility of a modification of J/ψ yield in high multiplicity pp events due to collective phenomena. It is also important to consider that a high energy proton-proton collision can have a substantial contribution from Multi-Parton Interactions (MPI). In this case several interactions on the parton level can occur in a single pp collision, which can introduce a dependence of particle production on the total event multiplicity. ALICE has recently measured the relative yield of J/ψ ($\frac{dN_{J/\psi}/d\eta}{\langle dN_{J/\psi}/d\eta \rangle}$) as a function of relative charged-particle multiplicity ($\frac{dN_{ch}/d\eta}{\langle dN_{ch}/d\eta \rangle}$). It can be seen from the Fig. 1.14 that the relative J/ψ yield increases faster than linear as compared to relative charged particle multiplicity both in mid-rapidity as well as in forward-rapidity.

The result has to be compared with the predictions of a model, which needs to reproduce all aspects of an event: the hard, the soft and semi-hard part of the event in a consistent framework. The J/ψ vs. multiplicity is com-

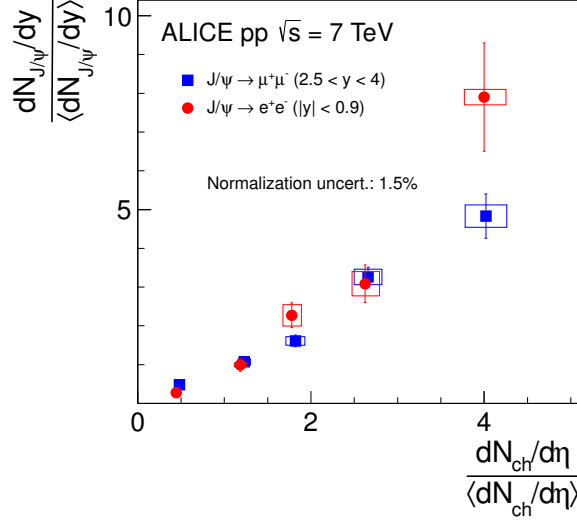


Figure 1.14. J/ψ yield as a function of the charged-particle multiplicity densities at mid-rapidity $dN_{ch}/d\eta$. Both values are normalized by the corresponding value for minimum bias pp collisions. J/ψ are measurements at forward rapidities ($2.5 < y < 4$) and at mid-rapidity ($|y| < 0.9$) [65].

pared with PYTHIA 6.4 which is shown in Fig.1.15. Implementation of MPI in PYTHIA 6.4 mainly affects processes involving only light quarks and gluons. Processes involving J/ψ and open heavy flavor production should not be influenced and their rates are expected to be independent of the overall event multiplicity. However, ALICE experiment has observed an increasing trend of J/ψ yield with multiplicity.

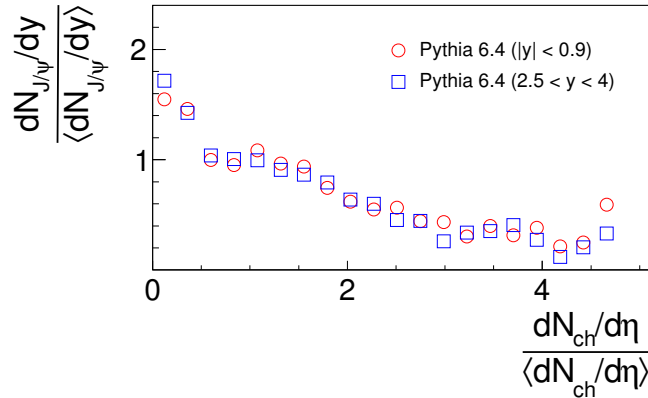


Figure 1.15. Relative J/ψ yield as a function of relative charged particle multiplicity densities around mid-rapidity $dN_{ch}/d\eta$ as calculated with PYTHIA 6.4 in the Perugia 2011 tune. J/ψ are measurements at forward rapidities ($2.5 < y < 4$) and at mid-rapidity ($|y| < 0.9$) [65].

At the LHC with very high collision energy, the number of interactions in proton+proton collisions depend on the impact parameter (b), where proton is thought to be an extended object. Therefore matter distribution inside hadron (proton) is introduced. So small impact parameter leads to large multiplicity and hence more MPIs. Therefore, at the LHC, a new QCD regime can be reached, where MPIs occur with high rates, due to unprecedentedly high parton densities in the colliding hadrons. Hence MPI, in particular can be redefined as soft or hard interaction, which can happen in parallel in a single pp collision. The very first interaction is hard in particular and the subsequent collisions can be semi-hard or soft. A schematic picture of MPI structure is shown in Fig. 1.16 for a better visualization. There is always a finite chance to produce heavy particle in first $2 \rightarrow 2$ collisions. But, the second interaction can produce heavy quarks like charm and bottom, if it is hard enough and this leads to a correlation between heavy-flavor and charged-particle multiplicity. If former is true, then the self normalized yield of J/ψ with respect to minimum bias as a function of charged-particle multiplicity should show a decreasing trend, which is observed in PYTHIA6 (Fig. 1.15). This is because, PYTHIA6 considers $2 \rightarrow 2$ interactions in hadronic collisions. If later is true, then only we can observe an increasing trend of self normalized J/ψ yield versus multiplicity.

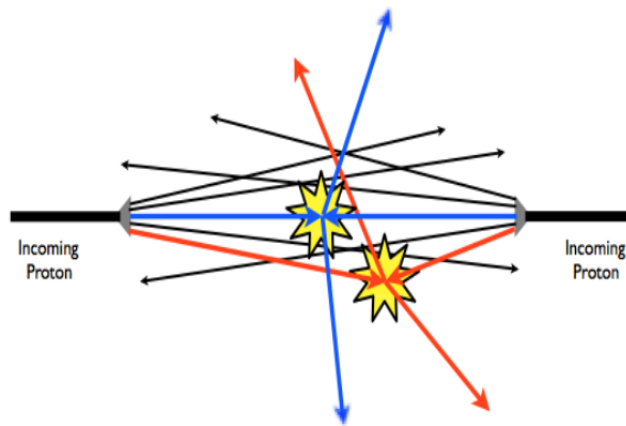


Figure 1.16. Event structure of a simple pp collision illustrating MPI.

Color reconnection and it's contribution to J/ψ production

The color flows are the separate subprocesses defined in the MPI scenario. As discussed in previous section, there is evidence that in pp collisions, multiple partonic interactions (MPI) may occur within the same collision. The partons belonging to two different MPI can be reconnected by color strings and merge into one in such a way that the total string length becomes as short as possible (to minimize string tension). An illustrative example of cartoon picture is shown in Fig.1.17.

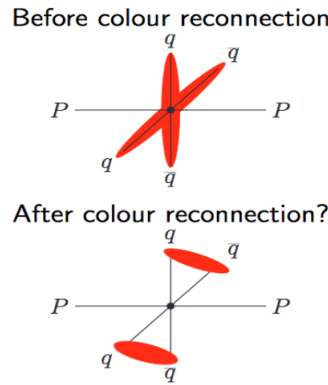


Figure 1.17. An illustrative example of color reconnection mechanism with string minimization.

The current version of PYTHIA8 uses different kind of color-reconnection model, namely [67]:

- **MPI-based CR model:** The partons of a lower- p_T MPI system are merged with the ones in a higher- p_T MPI.
- **Gluon motion CR model:** Partons can be moved from one location to another so as to reduce the total string length.
- **New scheme CR model:** The QCD color rules are used to determine the reconnection probability. The model also allows the creation of junction structures.

The increase of the average transverse momentum with the multiplicity can be described through the so-called color reconnection [64]. Different baryon to

meson ratios has been studied by models with and without CR and has been seen that the flow like pattern is well reproduced by CR [68]. One needs to introduce a flow like effect to obtain the peak structure in baryon to meson ratio and is well explained with CR. The origin of the flow like pattern (boost) is clearly different in CR compared to hydrodynamics. It is also remarked that CR produces the mass dependent rise of $\langle p_T \rangle$ as a function of multiplicity; therefore, radial flow is an important effect which plays a role to explain the CMS results [69]. As mentioned earlier, the present thesis deals with forward rapidity J/ψ production and contribution of underlying events which will be discussed in depth in subsequent chapters. Lets now look into another aspect of particle production at lower collision energies, i.e the effect of baryon stopping.

1.2 Creation of finite baryon density matter: Nuclear stopping power

A degree of stopping of colliding nuclei is one of the basic characteristics of the collision dynamics, which determines a part of the incident energy of colliding nuclei deposited into produced fireball and hence into production of secondary particles. The deposited energy in turn determines the nature of the produced fireball and thereby its subsequent evolution. Therefore to understand properly the baryon stopping is of prime importance for theoretical understanding of the dynamics of the nuclear collisions. A direct measure of the baryon stopping is the net-baryon rapidity distribution. However, since experimental information on neutrons is unavailable, proton is treated as a good proxy for baryons. Because baryon number is conserved, and rapidity distributions are only slightly affected by rescattering in the later stages of the collisions. The measured baryon distribution retains information about energy loss and allows the degree of nuclear stopping to be determined. At low energies like those at the AGS, the production of antiprotons is very small, so the net-proton distribution is assumed to be the same as the proton distribution and the rapidity distribution peaks at mid-rapidity. As the collision energy increases, a dip begins

to appear at midrapidity ($y \sim 0$) and the peak shifts toward the forward and backward rapidities, due to the production of anti-protons at mid-rapidity as shown in Fig.1.18. In mathematical concept, baryon-stopping can be understood as follow,

If incoming baryons have rapidity, $y_b = \ln(\sqrt{s_{NN}}/m_p)$, in the C.M. system, the average rapidity of an out going particle is determined as:

$$\langle y \rangle = \int_0^{y_b} y \frac{dN}{dy} / \int_0^{y_b} \frac{dN}{dy} \quad (1.16)$$

Therefore, the average rapidity loss is given by $\delta y = y_b - y$. Full transparency: $\delta y = 0$, no rapidity loss. Full stopping: $\delta y = 0$ approaches y_b , $\delta y = y_b$. Hence, the net-proton at the mid-rapidity can be used to quantify baryon stopping.

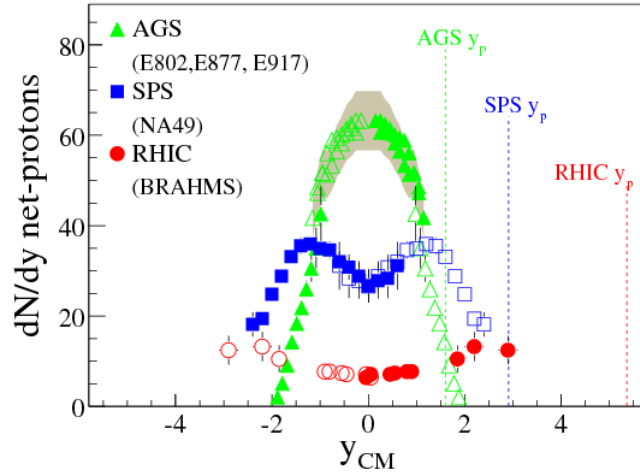


Figure 1.18. Rapidity density of net protons ($p - \bar{p}$) measured at AGS, SPS, and RHIC for central collisions. The figure is taken from Ref. [70].

Total number of protons detected in relativistic heavy-ion collisions is the sum of produced proton (and is equal to number of anti-proton) and number of stopped protons, i.e $N_p^{total} = N_p^{stop} + N_p^{produced}$. From the statistical treatment of particle production in heavy-ion collisions, if we neglect the decay contributions and consider only the primordial yield, the anti-particle to particle ratios are found to be controlled only by their respective fugacities. i.e

$$\frac{n_i}{\bar{n}_i} = \exp\left(\frac{2\mu_i}{T}\right). \quad (1.17)$$

For proton, the Eq. 1.19 can be written as,

$$\frac{N_p}{N_{\bar{p}}} = \exp\left(\frac{2\mu_B}{T}\right) \implies \mu_B = \frac{T}{2} \ln\left(\frac{N_p}{N_{\bar{p}}}\right). \quad (1.18)$$

Therefore,

$$\mu_B = \frac{T}{2} \ln\left(\frac{N_p^{stop} + N_p^{produced}}{N_{\bar{p}}}\right) \implies \mu_B = \frac{T}{2} \ln\left(1 + \frac{N_p^{stop}}{N_{\bar{p}}}\right). \quad (1.19)$$

Hence, experimentally higher baryon density can be achieved by high baryon stopping.

1.3 Probing thermal properties from particle spectra using non-extensivity: The Tsallis statistics

Due to high multiplicities produced in A+A and p+p collisions, the statistical models are more suitable to describe the particle production mechanism. Such a statistical description of transverse momentum (p_T) of final state particles produced in high-energy collisions has been proposed to follow a thermalized Boltzmann type of distribution as given by [71],

$$E \frac{d^3\sigma}{d^3p} \simeq C \exp\left(-\frac{p_T}{T}\right). \quad (1.20)$$

To account for the high- p_T tail, a power-law in p_T has been proposed [72, 73], which empirically accounts for the possible pQCD contributions. Hagedorn proposed a combination of both the aspects, which describes the experimental data over a wide p_T range [74] and is given by

$$\begin{aligned}
E \frac{d^3\sigma}{d^3p} &= C \left(1 + \frac{p_T}{p_0}\right)^{-n} \\
&\longrightarrow \begin{cases} \exp\left(-\frac{np_T}{p_0}\right) & \text{for } p_T \rightarrow 0, \\ \left(\frac{p_0}{p_T}\right)^n & \text{for } p_T \rightarrow \infty, \end{cases} \quad (1.21)
\end{aligned}$$

where C , p_0 , and n are parameters. This becomes a purely exponential function for small p_T and a purely power-law function for large p_T values. A finite degree of deviation from the equilibrium statistical description of identified particle p_T spectra has already been observed by experiments at RHIC [75, 76] and LHC [77–80]. Contrary to a thermalized system, where the $\langle p_T \rangle$ is associated with the temperature of the hadronizing matter, one fails to make such a connection in case of systems which are far from thermal equilibrium. In the latter systems, either the temperature fluctuates event by event or within the same event [81]. This creates room for possible description of the p_T spectra in high-energy hadronic and nuclear collisions, using the non-extensive Tsallis statistics. A thermodynamically consistent non-extensive distribution function is given by [82]

$$f(m_T) = C_q \left[1 + (q-1) \frac{m_T}{T}\right]^{-\frac{1}{q-1}}. \quad (1.22)$$

Here, m_T is the transverse mass and q is called the non-extensive parameter- a measure of degree of deviation from equilibrium. Eqs. 1.21 and 1.22 are related through the following transformations for large values of p_T :

$$n = \frac{1}{q-1}, \text{ and } p_0 = \frac{T}{q-1}. \quad (1.23)$$

Tsallis statistics is used widely to explain the particle spectra in high energy collisions starting from elementary $e^+ + e^-$, hadronic and heavy-ion collisions. The produced particles from the collisions carry the information about collision dynamics and the subsequent space-time evolution till the occurrence of the final freeze-out. The evolution of the partonic system created in high energy experiments is generally believed to be best described by hy-

drodynamics of an almost ideal fluid. This approach gives a fair description of data on the transverse momentum spectra of hadrons, which are treated as one of the important tools to understand the production dynamics of particles in high-energy collisions. The systematic analysis with the help of an appropriate model or approach guides us to understand various thermodynamical properties of the fireball at different stages of its evolution. The integrated yields of various hadronic species at different center-of-mass energies are used in the present work. The corresponding freeze-out parameters for each hadronic species at the time of their freeze-out can be obtained from the analysis of their respective transverse momentum distributions. Different forms of Tsallis distributions are used in this work to study the temperature (T), chemical potential (μ), radial flow (β), volume (V) and non-extensive parameter (q). In the present work, through a detailed spectral analysis, we study the freeze-out properties and make a connection of pp collisions with that of peripheral heavy-ion collisions.

Chapter 2

ALICE at the LHC

ALICE (A Large Ion Collider Experiment) [83] is one of the four major experiments at the Large Hadron Collider (LHC) [84] accelerator complex, mainly dedicated for heavy-ion physics. It is designed to study the physics of strongly interacting matter at extreme energy densities and temperatures, where a deconfined state of matter called Quark-Gluon Plasma (QGP) is expected to be formed. The study of the properties of such a state of QCD matter is the main goal of the ALICE experiment. Nevertheless, proton-proton (pp) collisions also play an important role in the ALICE physics program by providing a crucial reference for the QGP-related measurements and a fundamental testing ground of QCD predictions. Therefore, ALICE detector is designed for both heavy-ion as well as pp physics programs.

2.1 The Large Hadron Collider (LHC)

The Large Hadron Collider (LHC) [84] is the world's largest and most powerful particle accelerator. The LHC consists of a 27-kilometer ring of superconducting magnets with a number of accelerating structures to boost the energy of the particles along the way. LHC has achieved a center-of-mass energy of 5.02 TeV for Pb-Pb collisions and 13 TeV for pp collisions with its powerful machine, the highest center-of-mass energies ever achieved in laboratory. The beam particles/ions are guided around the accelerator ring by a strong magnetic field maintained by superconducting electromagnets. The high center-of-mass energies, that can be reached, require the use, among other things, of superconducting dipole magnets. This requires chilling the magnets to -271.3C ; a

temperature colder than the outer space. For this reason, much of the accelerator is connected to a distribution system of liquid helium, which cools the magnets, as well as to other supply services.

CERN's Accelerator Complex

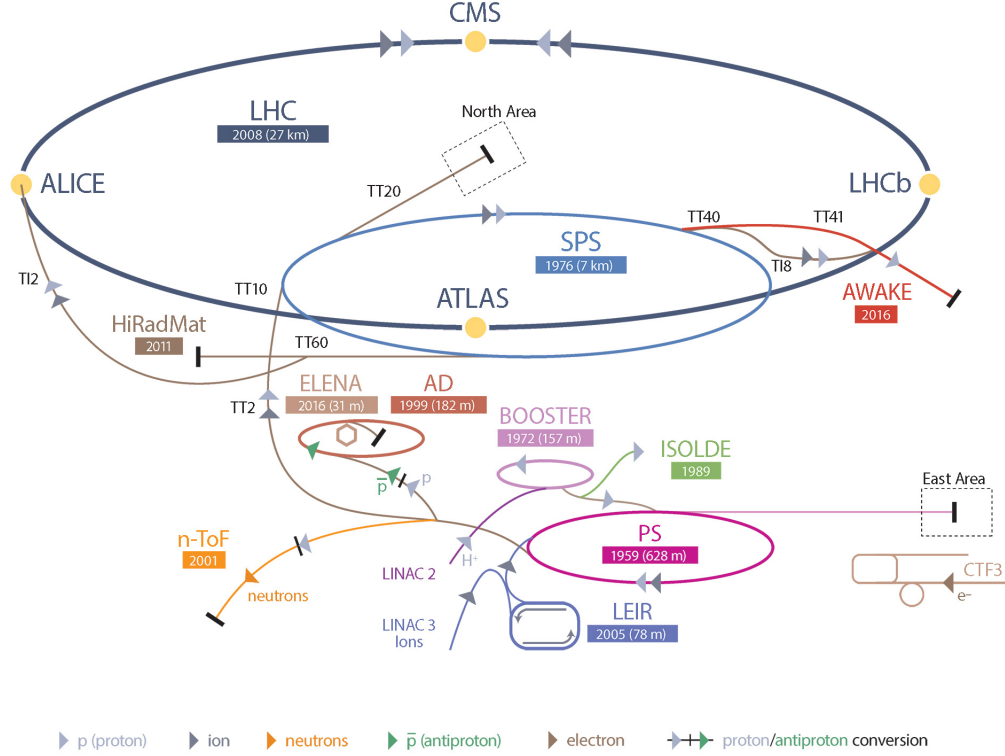


Figure 2.1. A schematic of CERN accelerator complex [85–87].

The LHC can accelerate two counter-rotating beams circulating in two separate beam pipes and collide in eight different points. In this thesis, four major experiments installed in four of the eight interaction points for a specific physics study are briefly discussed below,

- **ATLAS(A Toroidal LHC ApparatuS)** [89] is a general-purpose detector. The ATLAS detector has a large superconducting toroidal magnet. The detector surrounds entirely the collision point with an enclosed detector. ATLAS focused on the search for the Higgs boson, as well as on physics beyond the Standard Model like extra dimension, super symmetry etc.

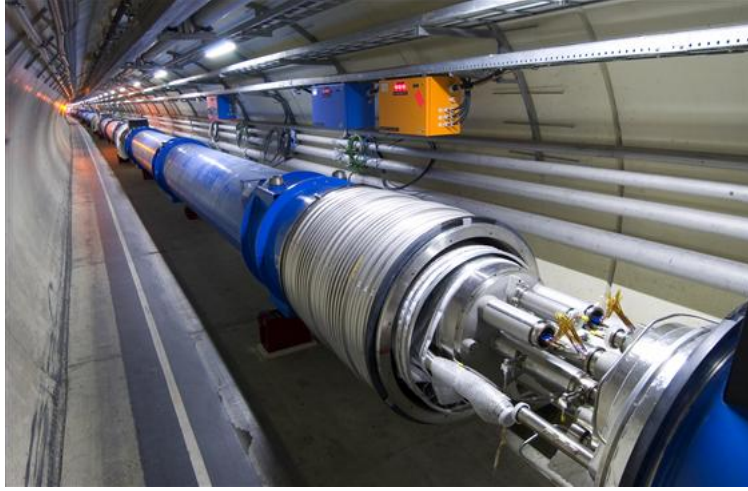


Figure 2.2. A small part of LHC ring. The blue cylinders contain the magnetic yoke and coil of the dipole magnets together with the liquid helium system required to cool the magnet so that it becomes superconducting [88].

- **CMS (Compact Muon Solenoid)** [90] is another general-purpose detector. The CMS detector is built around a huge solenoid magnet. It's also an enclosed detector with same physics aim as that of ATLAS detector.
- **LHCb (Large Hadron Collider beauty)** [91] detectors are mainly situated in the forward direction to detect forward particles. The experiment focuses on beauty (bottom) detection for precise measurements of matter anti-matter symmetry and rare decays.
- **ALICE (A Large Ion Collider Experiment)** [83] experiment is specifically designed to study heavy-ion collisions. It mainly focuses on physics of QGP. Detailed about the ALICE experiment is discussed in the next section.

2.2 The ALICE detectors

The ALICE experiment [84] is a general-purpose heavy-ion experiment which is sensitive to the majority of known physics observables and able to detect photons, hadrons, electrons and muons. It performs measurements in pp, p-Pb and Pb-Pb collisions as part of its physics program. The experiment has a high

detector granularity to cope with the high particle densities in central Pb-Pb collisions. The detector consists of two main parts.

- **The central barrel detectors** are embedded inside a solenoidal magnet with magnetic field $B = 0.5$ T, and is used for identification of charged-particles (ITS, TPC, TRD, TOF, HMPID) and photons (PHOS and EM-CAL).
- **The forward detectors**, namely, FMD, PMD, VZERO, TZERO, and ZDC are used for luminosity measurement, event characterization (centrality etc.) and triggering, along with other specific physics properties. In addition to these detectors, the **Muon Spectrometer** is one of the important detectors in the forward region of ALICE, which is responsible for muon tracking and triggering.

A schematic diagram of the ALICE with its subsystems is shown in Fig. 2.3. The co-ordinate system of ALICE is chosen in such a way that the origin is located at the interaction point (IP). The z-axis is parallel to the beam axis. A-side is positive and C-side is the negative direction of z-axis (e.g. Muon Spectrometer is located at C side). The x-axis is perpendicular to the beam line and points to the center of the LHC ring, and the y-axis points upward.

2.2.1 The Central barrel detectors

Inner Tracking System (ITS)

The Inner Tracking System (ITS) [93] of the ALICE experiment is made out of six cylindrical layers of silicon detectors exploiting three different technologies (pixel, drift and strip). It covers the central pseudorapidity range of $|\eta| < 0.9$ and its distance from the beam line ranges from $r = 3.9$ cm for the innermost pixel layer up to $r = 43$ cm for the outermost strip layer. The silicon detectors feature a high granularity and excellent spatial precision required due to the high particle density. Therefore, the first two layers are Silicon Pixel Detectors

THE ALICE DETECTOR

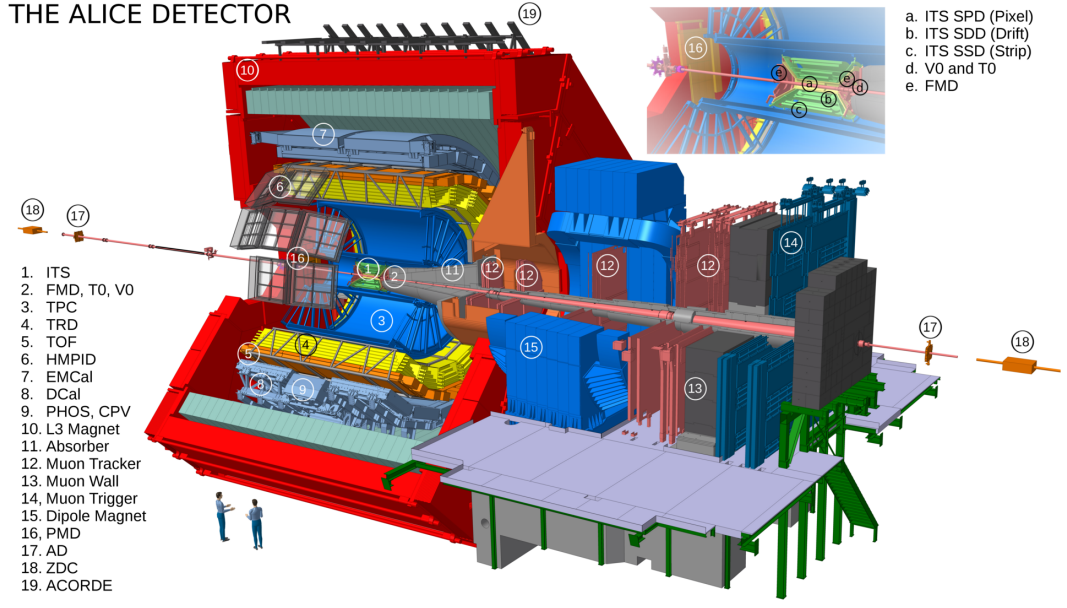


Figure 2.3. A schematic diagram of ALICE detector used for RUN2 [92].

(SPD) and the two following are Silicon Drift Detectors (SDD) (as the density of particle get smaller at larger radii). The main tasks of the ITS are to reconstruct the primary and secondary vertices, to track and identify charged particles with a low- p_T cutoff and to improve the momentum resolution at high- p_T . A schematic picture of ITS with its distinct layers are shown in Fig. 2.4.

Considering SPD as one of the most relevant detector used for the work performed in this thesis, this has been extensively discussed in the following sub section.

Silicon Pixel Detector (SPD)

As discussed earlier, the Silicon Pixel Detector (SPD) is part of the Inner Tracking System (ITS) of the ALICE experiment. The SPD consists of two layers of silicon pixel detector modules located around the beam-pipe at an average distances of 39 mm and 76 mm from the beam axis with a pseudorapidity coverage of $|\eta| < 2$ and $|\eta| < 1.4$, respectively. It contains a total of $\approx 10^7$ pixel

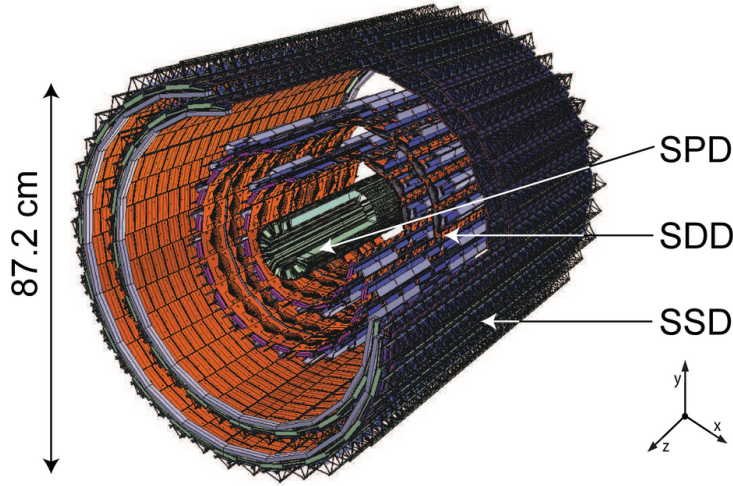


Figure 2.4. A schematic diagram of ITS component of ALICE detector [93].

cells. Further details on the detector design and the expected performance can be found in Ref. [94]. The reconstructed signals (tracklets) by SPD is used to estimate the number of primary charged particles produced both in collisions at ALICE. SPD has some basic advantages, such as a larger acceptance coverage both in pseudorapidity and p_T (down to 30 MeV/c) and a much smaller reliance on alignment and calibration procedures. This makes the measurement with SPD tracklets suitable to extract results from the very first available data from the LHC.

In this section, we would like to take the opportunity to give a brief description about tracklets reconstruction algorithm, which will very often come into the context in the data analysis chapter (chapter 3). The reconstructed points of the SPD and the reconstructed main vertex position are needed to build tracklets, where the primary vertex is reconstructed using SPD clusters as well. As shown in Fig. 2.5, a straight line from the vertex to each cluster in the inner layer is constructed. For each cluster in the inner layer two differences, namely $\Delta\theta$ and $\Delta\phi$ are computed using the reconstructed vertex as the origin. The two major task of SPD includes,

- **Tracklets finding** [95] Tracklets are reconstructed from SPD clusters.

To estimate tracklets, associate each cluster on layer1 to each cluster

on layer2 within an window of $\Delta\phi$. The procedure is repeated for each cluster in the inner layer so that each cluster can be associated only once. Clusters in the outer layer can either be used in one tracklet only or in more than one. Fig.2.5 shows illustratively the calculation of $\Delta\phi$.

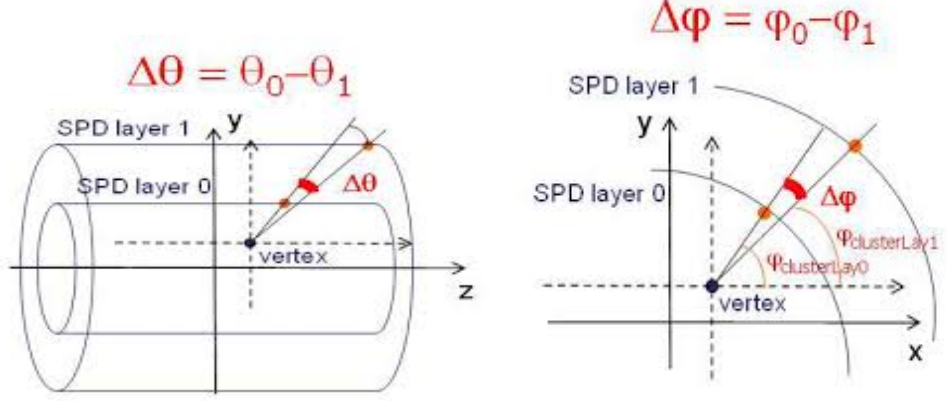


Figure 2.5. Full and transverse plane view of the detector showing how $\Delta\theta$ and $\Delta\phi$ are calculated [95].

- **Vertex finding [95]:** The distance of closest approach between a tracklet and the nominal beam position, Z_i , is calculated and then the distribution of Z_i is used to find the collision vertex. The Region Of Interest (ROI) around the peak of the Z_i distribution is defined (ΔZ) and vertex position is calculated by taking weighted mean in the ROI.

$$z_{mean} = \frac{\sum_{n=i}^N \frac{Z_i}{\sigma_i}}{\sum_{n=i}^N \frac{1}{\sigma_i}} \quad (2.1)$$

The uncertainty, σ_{vertex} , is calculated by the propagation of error for the cluster. The default widths of the cut windows for pp events are $\Delta\phi_{cut} = 0.08$ radian and $\Delta z_{cut} = 1$ cm respectively.

The ITS design allows to localize the primary vertex with a resolution better than $100 \mu\text{m}$, reconstruct the secondary vertices from the decay of hyperons: D and B mesons track and identify low momentum particles ($p < 100$

MeV/c) and, finally, complete and improve the information provided by the TPC.

Time Projection Chamber (TPC)

The TPC [96] is one of the main charged particle tracking detectors in the central barrel with a pseudorapidity coverage , $|\eta| < 0.9$. The TPC is designed to provide charged-particle momentum measurements up to $p_T = 100$ GeV/c and vertex determination in the high-multiplicity environment. In addition to this, TPC provides particle identification via specific ionization energy loss up to a particle momentum of 1 GeV/c. The TPC is a cylindrical shape detector which has an inner radius of about 85 cm and an outer one of about 250 cm, with a total length of about 500 cm. The layout of TPC detector of ALICE is shown in Fig. 2.6. It is divided by the central High Voltage (HV) electrode into two drift regions of 250 cm. Each drift region has 18 sectors of read-out multi-wire proportional chambers (MWPC) mounted into the end plates. The detector is filled with a gas mixture of Ne, CO₂ and N₂. The charged particles traversing the detector ionize the gas. TPC has around 88 μ s drift time which is the limiting factor for the luminosity delivered to ALICE in proton-proton collisions. The study of soft hadronic observables requires a resolution of 1% for momenta between 100 MeV/c and 1 GeV/c, while the detection of hard probes requires a 10% resolution for tracks with $p_T = 100$ GeV/c. The latter can be achieved by using the TPC in combination with ITS and TRD.

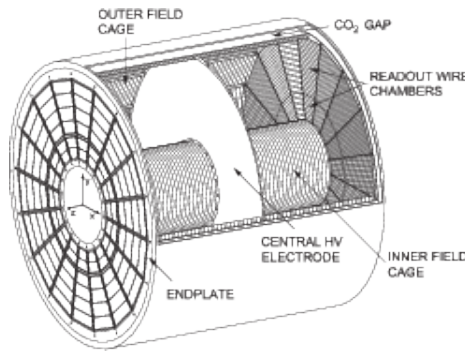


Figure 2.6. The layout of ALICE TPC detector [96]

Transition Radiation Detector (TRD)

TRD [97] covers the pseudorapidity range $|\eta| < 0.9$. This detector is used to provide charged-particle tracking, electron identification via transition radiation, pion rejection as well as triggering capability for high transverse momentum processes. In conjunction with TPC and ITS, it allows to measure the production of light and heavy vector meson resonances and the determination of the impact parameter, of open charm and beauty. A similar technique is used to separate the promptly produced J/ψ mesons from those produced via B-decays (non-prompt). TRD consists of 18 sectors of 6 layers each with a 5-fold segmentation along the beam direction, for a total of $18 \times 6 \times 5 = 540$ detector modules. Each module consists of a radiator of 4.8 cm thickness, a multi-wire proportional readout chamber and its front-end electronics.

Time of Flight (TOF)

The TOF [98] is a cylindrical detector with an inner radius of 3.7 m with the pseudorapidity coverage of $|\eta| < 0.9$. The large coverage requires the use of a gaseous detector: Multi-gap Resistive Plate Chambers (RPC), providing an intrinsic time resolution of better than 40 ps and an efficiency close to 100%. The TOF detector is used for particle identification in the intermediate momentum range, from 0.2 to 2.5 GeV/c. Combined with the ITS and TPC it provides an event-by-event identification of large samples of pions, kaons and protons.

High Momentum Particle Identification Detector (HMPID)

HMPID [99] is designed as a single-arm array with a pseudorapidity acceptance of $|\eta| < 0.6$ and an azimuthal coverage of about 58° which corresponds to 5% of the central barrel phase space. The detector is based on proximity-focusing Ring Imaging Cherenkov counters and consists of seven modules of about $1.5 \times 1.5 \text{ m}^2$ each. The HMPID performs inclusive measurements of identified hadrons at $p_T > 1 \text{ GeV}/c$. It is optimised to enhance the particle identification

capabilities of ALICE. The HMPID can make π/K and K/p discrimination on a track-by-track basis up to 3 GeV/c and 5 GeV/c respectively. It can also perform identification of light nuclei and anti-nuclei at high momenta.

PHOton Spectrometer (PHOS)

The PHOS [100] is a single-arm spectrometer including a highly segmented electromagnetic calorimeter made of lead-tungstenate crystals and a charged particle veto detector consisting of a Multi-Wire Proportional Chamber with cathode-pad readout. PHOS covers pseudorapidity range of $|\eta| < 0.12$ and 100° in the azimuthal angle. The PHOS is designed to provide photon identification, as well as neutral meson identification, through the two-photons decay channel.

ElectroMagnetic Calorimeter (EMCal)

EMCAL [101] is a layered lead (Pb) scintillator sampling calorimeter with alternating layers of 1.44 mm of lead and 1.76 mm of scintillator. It covers a pseudorapidity range of $|\eta| < 0.7$ and 107° in azimuth. EMCal enhances the ALICE capabilities for high-energy jet measurements by improving jet energy resolution. It also augments the capabilities to measure high momentum photons and electrons.

2.2.2 The Forward detectors

Forward Multiplicity Detector (FMD)

The FMD [102] provides charged particle multiplicity informations in the pseudorapidity range $-3.4 < \eta < -1.7$ and $1.7 < \eta < 5.1$. FMD consists of silicon strip detectors divided in seven disks perpendicular to the beam pipe and placed at distances between 42 and 225 cm from the interaction point (IP).

Photon Multiplicity Detector (PMD)

The Indian detector, Photon Multiplicity Detector (PMD) [103, 104] is designed to measure photon multiplicity and spatial ($\eta - \phi$) distribution of photons, on an event-by-event basis, in the forward region ($2.3 < \eta < 3.7$). PMD is placed at about 360 cm from the interaction point, in the side opposite to the Forward Muon Spectrometer. Fig. 2.7 shows the position and layout of the PMD. It consists of two identical planes of detectors, made of gas proportional counters with honeycomb cell structure and wire readout, with a $3X_0$ ¹ thick lead converter in between. A photon passing through the converter plate produces an electromagnetic shower in the pre-shower plane, which leads to a large signal spread over many cells. Whereas the signal from a charged particle is confined mostly to a single cell, this response allows to reject the charged particles tracks [103].

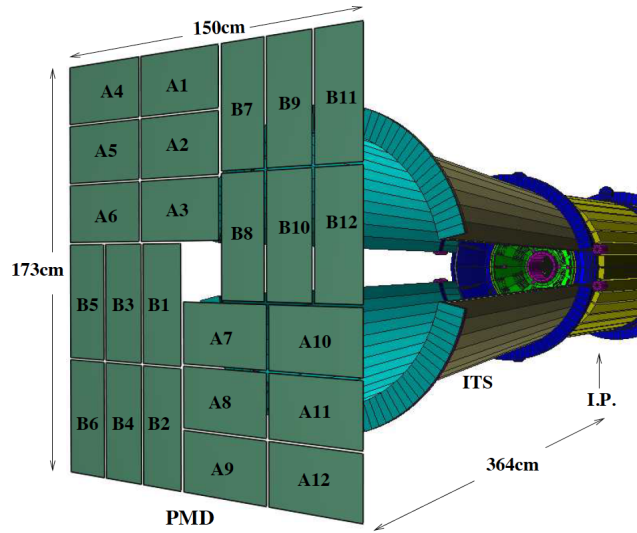


Figure 2.7. The PMD position and layout in ALICE shown with respect to the ITS [103].

¹The radiation length, X_0 , is a characteristic of a material, defined as the mean traversed distance by which a high-energy electron loses all but $1/e$ of its energy.

VZERO Detector (V0)

VZERO [102] detector is composed of two arrays, VZERO-A and VZERO-C, which cover the pseudorapidity ranges $2.8 < \eta < 5.1$ and $-3.7 < \eta < -1.7$ for collisions at the nominal vertex ($z = 0$). The measurement of the time-of-flight difference between the two detectors allows to identify and reject the beam-gas events, thus providing a minimum bias (MB) trigger for the central barrel detectors and a validation signal for the muon (μ -MB) trigger. The VZERO detector is also used for the measurement of charged particle multiplicity and hence the centrality estimation.

T0 Detector

The T0 [102] detector consists of two arrays (T0-A and T0-C) of Cherenkov counters with the interaction point (IP) in-between. The distance from the IP to T0-C is 70 cm while on the opposite side the distance from T0-A to the IP is about 3.6 m. T0-C covers the pseudorapidity range $2.9 < \eta < 3.3$ and T0-A of $4.5 < \eta < 5$. The T0 detector is designed to fulfill the following functions:

- To supply main signals to the ALICE L0 ¹trigger
- To deliver an early (prior to L0 trigger) wake-up to TRD
- To give a precise start signal for time-of-flight (TOF) particle identification

Zero Degree Calorimeters (ZDCs)

The ZDCs [105] are calorimeters which detect the energy of the spectator nucleons (nucleons which do not participate in the collision) in order to determine the overlap region of the two colliding nuclei. It is composed of four calorimeters, two to detect protons (ZP) and two to detect neutrons (ZN). They are located 115 m away from the interaction point (IP) on both sides along the beam line. That is why we call them Zero Degree Calorimeters (ZDC). The

¹Detailed about L0 trigger is discussed in the section 2.2.3

ZDC system also presents two electromagnetic calorimeters (ZEM), both placed at about 7 m from the IP, allow to resolve ambiguities in the determination of the centrality.

Forward Muon Spectrometer

The Forward Muon Spectrometer of ALICE [106, 107] is mainly designed to measure the production of heavy quarkonia (J/ψ , $\psi(2S)$, $\Upsilon(1S)$, $\Upsilon(2S)$ etc.) as well as the low mass mesons (ρ , ω , ϕ) via their dimuon ($\mu^+\mu^-$) decay channel. The detector is also used to measure the production of single muons from decays of heavy flavor hadrons (D and B mesons) and the $W^\pm$ and Z^0 bosons. The spectrometer has angular acceptance between $171^\circ < \theta < 178^\circ$ corresponding to a pseudorapidity range $-4 < \eta < -2.5$ which provides good acceptance down to zero transverse momentum and a manageable background from hadron decays, where the J/ψ contribution coming from B hadron decays is lower. In order to separate all resonance states, particularly in the bottomonium mass range, a resolution of 100 MeV/c² is needed. The detector consists of the following components:

- a system of passive absorbers
- ten high granularity detection planes (arranged in five stations)
- a dipole magnet
- a passive iron wall
- four trigger chambers (arranged in four stations).

Schematic pictures of ALICE Forward Muon Spectrometer are presented in Fig. 2.8 and 2.9. The details about different parts of the spectrometer is described in following sections.

System absorber and shielding: The large background environment in central Pb-Pb collisions requires absorbers and shielding in the Muon Spectrometer. The Muon Spectrometer contains four separated parts: the front absorber, the beam shield, the iron wall and the rear absorber.

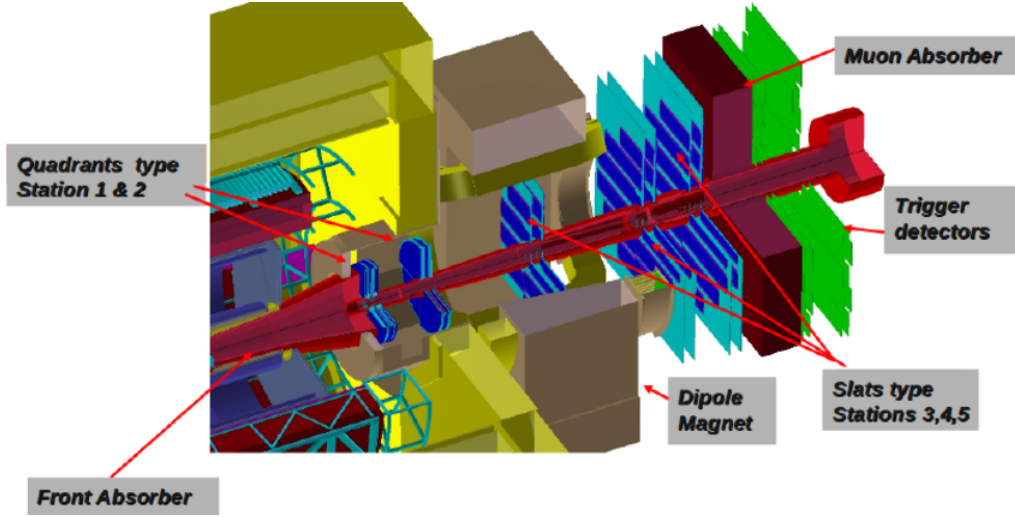


Figure 2.8. 3D view of ALICE Forward Muon Spectrometer [108].

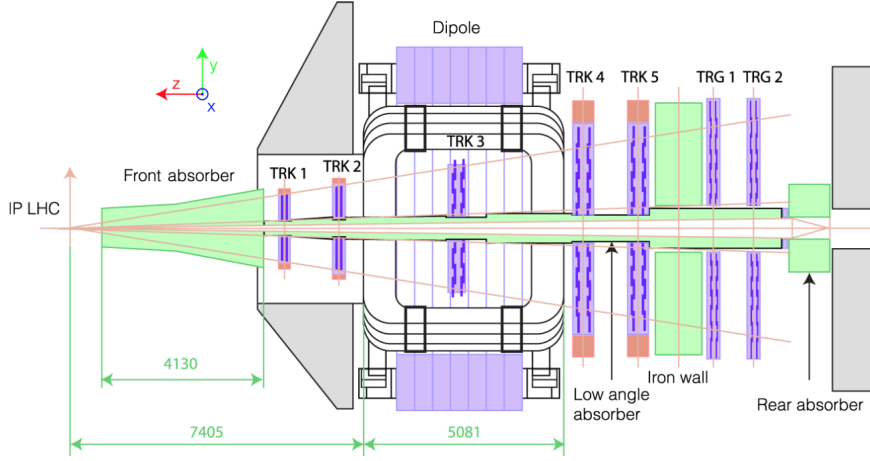


Figure 2.9. Schematic view of the ALICE Forward Muon Spectrometer [109]

- **Front absorber:** The front absorber, shown in Fig. 2.10, is located inside the ALICE solenoid magnet L3 and has a total length of 4.13 m (corresponding to $\sim 10 \lambda_{int}$ ¹ interaction and ~ 60 radiation lengths X_0 ²). The absorber design is optimized to provide a good shielding of hadrons from the IP and background from $\pi, K \rightarrow \mu$. Also, it limits the multiple scattering of the muons which should not compromise the spectrometer mass resolution on the other hand. Fig. 2.10 shows a layout of the front

¹ λ_{int} is the nuclear interaction length, defined as the mean path length required to reduce the number of relativistic charged particles by the factor $1/e$, or 0.368, as they pass through matter.

² The radiation length, X_0 , is a characteristic of a material, defined as the mean traversed distance by which a high-energy electron loses all but $1/e$ of its energy.

absorber. The region close to the IP is made of a low Z material, Carbon, in order to reduce multiple scattering effects. The rear part is made of concrete and several layers of lead and boronated polyethylene to absorb the secondary particles produced in the absorber and low energy protons and neutrons. The external coating of the absorber is lead and boronated polyethylene to avoid the recoil particles to reach the TPC. There is an inner shield covering the beam, made of tungsten to absorb the background particles from beam-gas interactions

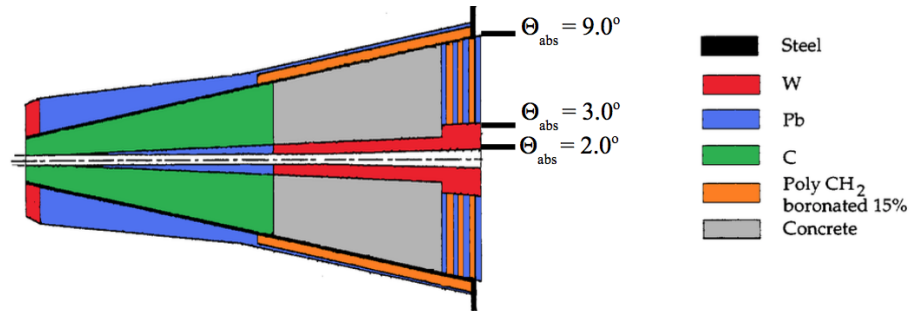


Figure 2.10. Schematic view of front absorber of the ALICE Forward Muon Spectrometer [106]

- **Beam shield:** The small-angle beam shield protects the tracking chambers by reducing background particles produced in the beam pipe. It is made up tungsten, lead and stainless steel. It has a conical geometry along the length of the spectrometer, follows the 178° acceptance line up to a maximum radius of 30 cm.
- **Iron wall:** While the front absorber and the beam shield are sufficient to protect the tracking chambers, the trigger chambers require additional protection. For this reason the muon filter, an iron wall 1.2 m thick ($\sim 7.2\lambda_{int}$), is placed after the last tracking chamber, in front of the first trigger chamber. Due to the presence of the front absorber and muon filter, muons with momenta less than 4 GeV/c are stopped.
- **Rear absorber:** This is the additional shielding at the back of the trigger chambers to protect from beam gas interactions produced in the LHC beam pipe at the LHC tunnel.

Dipole magnet: The dipole magnet of the Muon Spectrometer is used to measure the momentum and electric charge of the muon. The size of the magnet is 5 m length 7.1 m width 9 m height with a total weight of about 890 tons. It covers the angular acceptance of $171^\circ < \theta < 178^\circ$. The dipole magnet is placed at 7 m from the IP and provides a central magnetic flux density of 0.67 T and an integrated value of 3 Tm. The direction of the magnetic field is perpendicular to the beam direction, which defines the bending (yz -plane) and non-bending (xz -plane) plane. The naming is based on bending of muon and yz plane is called bending plane because the muons are deviated along the yz -plane.

Muon Tracking Chamber: The muon tracking chamber (MCH) is responsible for reconstructing the muon trajectories. It consists of five stations with two Cathode Pad Chambers in each station. Given the magnetic field provided by the dipole, the muon tracking system is required to have a spatial resolution better than $100\ \mu\text{m}$ in the bending plane to achieve the mass resolution that can separate bottomonium states, whereas the spatial resolution is 1 mm in the non-bending one. To limit the multiple scattering on the particle trajectories, the chamber thickness had to be as small as a few percent of radiation length per plane. The chambers are Multi-Wire Proportional Chambers (MWPC) with cathode pad as readout. The space between the cathode planes are filled with a 80% Ar and 20% CO_2 gas mixture. Such chambers are called Cathode Pad Chambers (CPC). The anode wires of the MWPC are connected to high voltage while the cathode pads are grounded. A charged-particle while passing through the active gas volume, ionizes the gas along its trajectory. The electrons drift towards the nearest anode wire where they generate an avalanche of secondary electrons. The resulting ion cloud induces a charge distribution on the cathode pads close to the avalanche position. The distribution of charge in the pads of the bending and non-bending planes allow to determine the position where the charged particle traversed the chamber. A schematic picture of the explained mechanism in MWPC is shown in the Fig. [2.11](#).

To measure the muon momenta, it's necessary to determine at least, two points of the muon candidate track before the magnetic field and two after. The

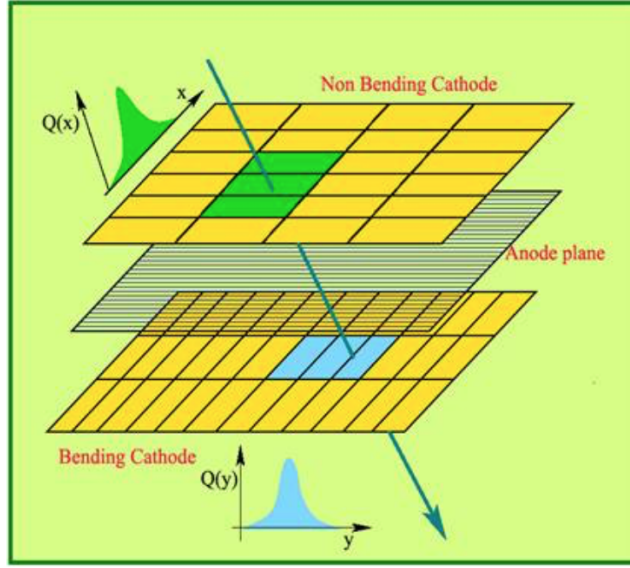


Figure 2.11. Schematic picture of working principle of muon chamber MWPC [110].

fifth point is not mandatory for it. However, the fifth point would increase the precision on the sagitta. Hence, the use of five tracking chambers is strongly recommended. In order to have an even more robust tracking system against possible breakdown of wires and also to increase the detection efficiency, these five chambers were doubled and associated by pairs in stations. All the five stations are placed as: two before, one inside and two after the dipole magnet.

Muon Trigger System: The main purpose of muon trigger is to select events with high p_T muons produced in heavy quarkonia or open charm decays, and rejecting events with low p_T muons, which come mainly from π and K decays. The distribution of these background muons (muons from π and K) is peaked at low transverse momenta. To minimize the background, a low- p_T is applied on each individual muon at the trigger level. The p_T threshold can range from ~ 0.5 to ~ 4 GeV/c. In order to achieve this requirement, a large-area trigger system based on position sensitive detectors with a resolution of the order of a millimeter is needed. This can be achieved by use of Resistive Plate Chambers (RPC). The muon trigger system consists of four Resistive Plate Chambers (RPC) planes arranged in two stations (MT1) and (MT2) spaced 1m apart, and located after the iron muon filter. The main task of RPCs are to measure the time and position of charged particles crossing its active area.

A typical structure of the ALICE single-gap RPCs is shown in Fig. 2.12. The 2 mm thick gas gap (active volume) is enclosed between two parallel electrode plates. The outside faces of the plates are painted with graphite and one is connected to high voltage and the other is grounded. An insulating film covers the graphite electrodes and aluminum strips are placed at the outside of the chamber. Muon ionizes the gas when it passes through the chamber. Then the resulting electrons cause avalanche of secondary electrons along the whole gas volume. The electrodes are transparent to these electrons, so they are picked up by the aluminium strips. The Front End Electronics gathers the signal from the strips, which consists of a pattern of hit strips. The signal is sent to the local trigger board which gives a quick measure of the muon momentum.

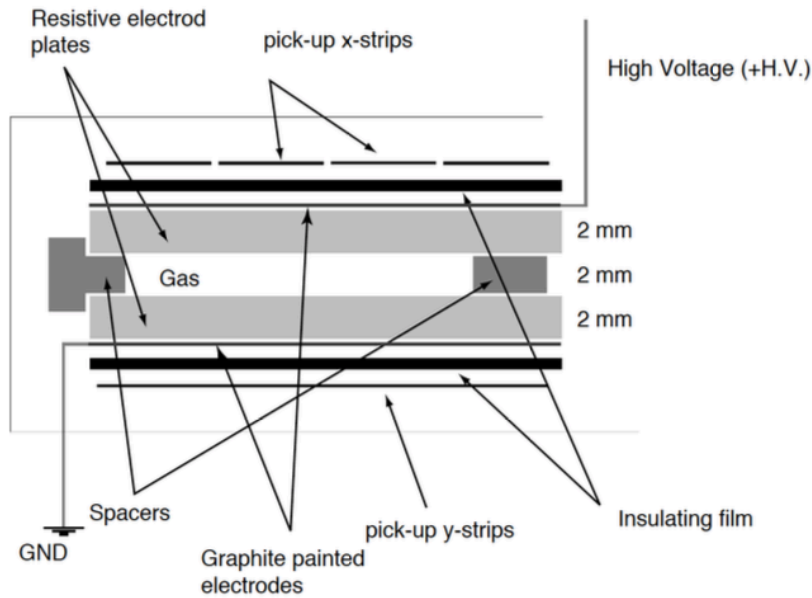


Figure 2.12. Schematic picture RPC cross section [83].

Trigger principle: The p_T cuts required to select high- p_T muons (muons emitted from heavy-flavors) is implemented in muon trigger system. A muon (blue line in the figure) is bent by dipole magnetic field and fires the two trigger station MT1 and MT2. The co-ordinates in bending $y-z$ plane are (y_1, z_1) and (y_2, z_2) , respectively as shown in the Fig. 2.13. The deviation induced along the y -direction by the dipole magnetic is given by,

$$\delta y_2 = y_2 - y_{2,\infty}, \quad (2.2)$$

where $y_{2,\infty}$ is the y -coordinate in which muon with infinite momentum crossing MT1 at y_1 would fire MT2. With small deviation (less than 10°), Eq. 2.2 can be written in term of muon p_T as,

$$\delta y_2 = (z_2 - z_1) \cdot \frac{eBL}{z_1} \cdot \frac{R_f}{p_T}, \quad (2.3)$$

where B is the dipole magnetic field, L is the dipole length and R_f is the estimated radial position. Therefore, δy_2 correspond to a cut on muon p_T .

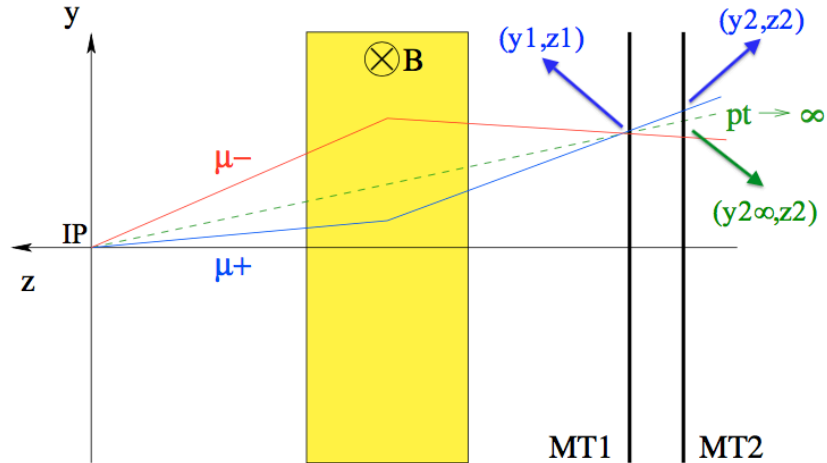


Figure 2.13. Illustrative picture to show Muon Spectrometer trigger principle [106].

2.2.3 ALICE trigger system, Control system and Data reconstruction

ALICE trigger system

Trigger system is necessary to start the detector read-out whenever an interesting event occurs. Moreover, for the current luminosities at LHC, more collisions take place than can be recorded. Thus, a trigger system is needed to select events of rare signals for physics interest. The ALICE trigger system [111] comprises of four different levels. Lower the level, faster is the decision of the event to be selected. Higher level triggers are set to select the events for the more complex analysis. The ALICE Central Trigger Processor (CTP) generates the trigger decision. It selects events depending on the physics requirements and the restrictions imposed by the bandwidth of the Data Acquisition (DAQ) system. The ALICE trigger is a 3-level system, level 0 (L0), level 1 (L1) and level 2 (L2).

- The trigger signal of the lowest level (level 0, L0) reaches the detectors after a delay of only 1.2 s and can provide simple information as whether there was a collision or what is its multiplicity. The L0 trigger inputs (L0b, b for “before the CTP”) are the first to arrive to the CTP. They are sent by detectors such as V0, T0, SPD, EMCAL, PHOS and MTR. The CTP sends a L0 trigger signal (L0a, a for “after the CTP”) to the corresponding read-out detectors in the trigger cluster.
- The L1 trigger inputs are sent to the CTP by detectors such as the TRD, ZDC and EMCAL after the online calculation of some characteristic of an event. The CTP makes a decision and sends a L1 trigger signal, which arrives to the read-out detectors with $6.5 \mu\text{s}$ delay. If the L1 trigger signal does not arrive on time to the read-out detectors they ignore the event.
- The subsequent trigger level L2 waits for the end of the so-called *past – future protection interval* to reject pile-up events. The length of this interval is essentially defined by the TPC readout time ($\sim 100 \mu\text{s}$). At

nominal LHC luminosities a pile-up of events is frequent. The L2 trigger logic has to take care of that its degree is still tolerable and the event has not been spoiled. The L2 delay time can also be used to apply more complex trigger algorithms. The final stage of the trigger system, the High Level Trigger (HLT), provides full online data reconstruction and analysis. By rejecting events based on this analysis and by applying compression algorithms without the loss of physics information, the HLT reduces the data volume significantly.

Control System

The ALICE experiment is centrally controlled by the Experiment Control System (ECS). It operates different online systems which include, the Data Acquisition (DAQ), the Trigger System (TRG), the High Level Trigger (HLT), and the Detector Control System (DCS). The DCS provides remote control and monitoring of all experimental equipment. A schematic picture of its organization is shown in Fig. 2.14. The central DCS top control unit is itself steered by the ECS or an operator and commands the DCS control units of all detectors. All units in the control tree are monitored by the above units. Each unit is special in itself with finite set of predefined states. Transitions between states are possible by executing actions. Such actions can be performed by an operator, another unit or by events as state changes of other components.

Data reconstruction

A high-precision alignment and calibration data are produced during the first pass reconstruction (**pass1**). The detector alignment and calibration data are stored in the Offline Condition Data Base (OCDB). With the data reconstruction information, a first set of Event Summary Data (ESD) is produced. The filtered data in the ESDs for specific analyses can be done to produce the first Analysis Object Data (AOD). Feedback from the pass1 data including inputs from analyses are used to reproduce **pass2** data.

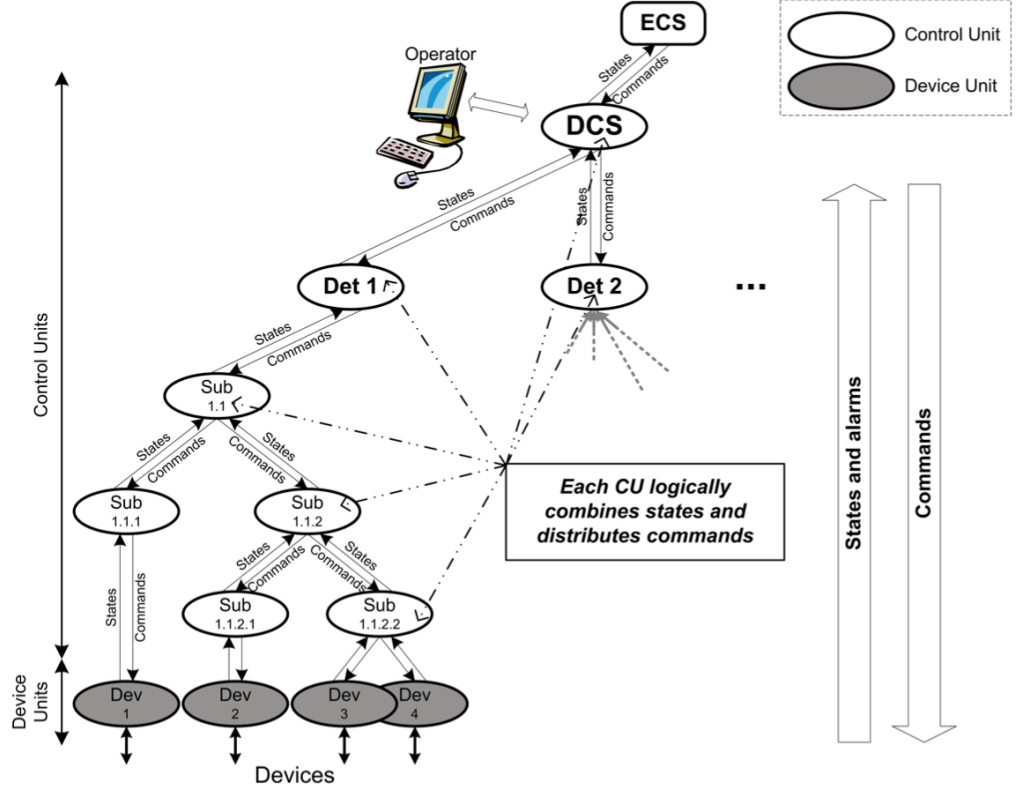


Figure 2.14. A schematic view of ALICE DCS structure [83]

2.3 Data sample selection

The data sample is collected in the year 2016. The present analysis is carried out using "pass1/AliAOD.Muons.root" from the data periods LHC16h¹, LHC16j, LHC16k, LHC16o, LHC16p. The good run numbers were selected on the basis of proposal from Data Preparation Group [112], where the central barrel detectors (SSD, SPD, SDD, V0) are involving in readout. Here, we have specifically taken in to consideration the muon quality and physics selection status from the Run Condition Table [113]. The run numbers used for the analysis corresponding to each periods are enlisted in appendix section. 8.3. As

¹The data taking periods naming convention is "LHC+year+letter"

discussed in previous sections, different triggers are activated during the data taking for different physics analysis. For the current analysis, we have used minimum bias (MB) trigger which is defined as the coincidence of signals in the VZERO-A and VZERO-C which is also techniqueally called as CINT7 trigger. The di-muon trigger used in this analysis is called CMUL7 and is defined as the MB trigger condition along with the coincidence of a di-muon signal. Along with these triggers, we have listed below other triggers which are also used for the muon analysis;

- **CMSL:** Single muon low- p_T (single muon with $p_T^\mu \leq 0.5$ GeV/c)
- **CMSH:** Single muon high- p_T (single muon with $p_T^\mu \geq 4$ GeV/c)
- **CMUL:** Unlike sign di-muon low- p_T (opposite charge muon pair with $p_T^\mu \geq 0.5$ GeV/c for each muon)
- **CMLL:** Like sign di-muon low- p_T (same charge muon pair with $p_T^\mu \geq 0.5$ GeV/c for each muon)

The corresponding L0 trigger inputs is defined by replacing “C” with “0” (e.g 0MSL, 0MUL etc.).

For the current analysis two type of triggers **CINT7-B-NOPF-MUFAST** ¹ and **CMUL7-B-NOPF-MUFAST** are used along with **kINT7inMUON** ² and **kMuonUnlikeLowPt7** ³ respectively.

2.3.1 Event Selection

The selected events are required to pass physics selection and have a reconstructed primary vertex with at least one primary vertex contributor. The details about the “Quality Assurance” cuts apply on the reconstructed vertex are discussed in section 3.1.1. The amount of background events in the data

¹The naming of the trigger classes includes the trigger name but also bunch crossing features (i.e. ”B” meaning beam-beam, ”S” meaning beam-satellite), CTP vetoes (i.e. NOPF meaning no past-future protection activated) and trigger cluster name (i.e. MUON which contains SPD, MTR and MCH).

²INT7 in MUON or MUFAST cluster

³Unlike-sign di-muon low-pt, INT7 suite

List of triggers used for the analysis			
LHC Periods	Triggers	Trigger description	Counts (with cuts)
16h+16j+16k +16o+16p	CMUL7-B-NOPF- MUFAST	Dimuon low p_T , both the muon with $p_T^\mu > 1$ GeV/c	102125200
16h+16j+16k+16o+16p	CINT7-B-NOPF- MUFAST	Minimumbias (VZERO AND)	28975090

Table 2.1.

sample after the application of physics selection cut is negligible. The counts on each trigger class considered in this analysis, for physics selected events along with the required analysis selections (cuts) are listed in Table. 2.1.

2.3.2 Track selection cuts

Only the events passing Physics Selection are taken in to consideration for the present analysis. Standard cuts are applied on the opposite sign dimuons and single muon track level. These are listed below,

- Rapidity cuts on the dimuon, $-4.0 < y_{\mu\mu} < -2.5$ to cope with the muon spectrometer acceptance
- Pseudo rapidity cuts on both the muons(separately) belonging to dimuon, $-4.0 < \eta_\mu < -2.5$ to reject tracks at the edges of the acceptance
- The radial transverse position of the muon tracks at the edges of the acceptance(R_{abs}), $17.6 < R_{abs} < 89.5cm$ to remove tracks crossing the thicker part of the absorber
- Both the muon tracks should match the low p_T trigger that defines the CMUL conditions (muon pairs with opposite sign)

2.4 Analysis strategy for J/ψ versus charged-particle multiplicity study

The study of J/ψ as a function of charged-particle multiplicity comprises of two parts: determination of charged-particle multiplicity using SPD tracklets and measurements of J/ψ (yield and $\langle p_T \rangle$) via dimuon channel. A brief description of the steps followed for the complete study is illustrated in the flowchart 2.15. We have organized this analysis in two parts: the chapter 3 is dedicated to multiplicity estimation and chapter 4 contains J/ψ measurement and the physics results.

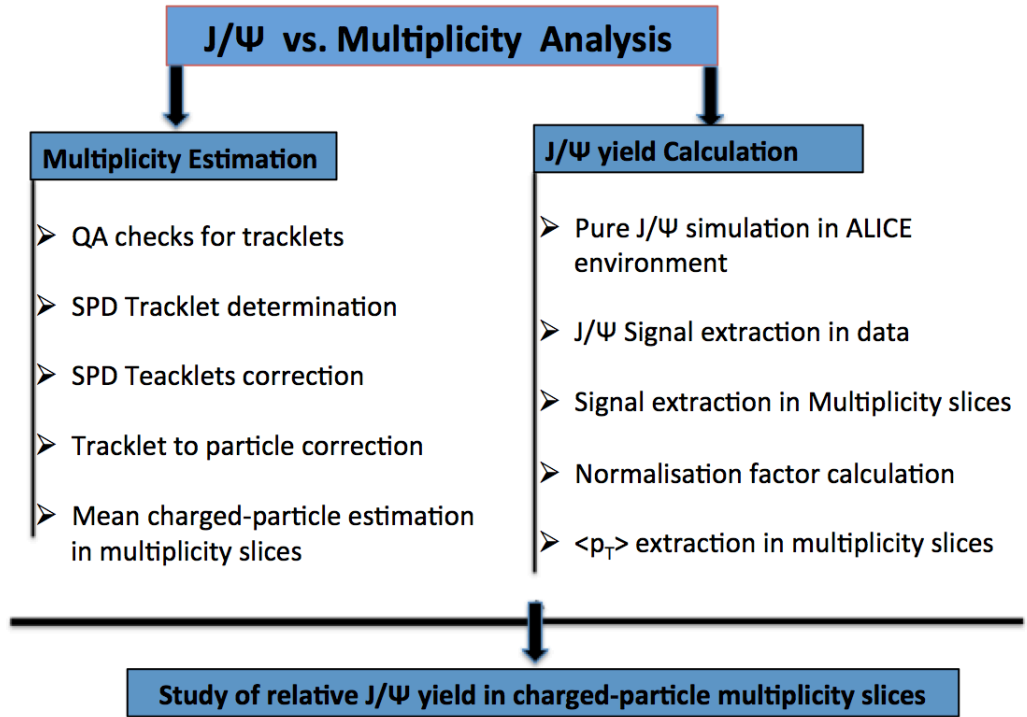


Figure 2.15. Analysis flow-chart

Chapter 3

Data analysis: Estimation of charged-particle density

¹In this chapter, the estimation of charged particle multiplicity is discussed, i.e. the number of primary charged particles produced in the collision. Primary particles are defined as prompt particles produced in the collision, including decay products, except those from weak decays of strange particles. In this chapter the charged-particle pseudo-rapidity density, $dN_{ch}/d\eta$, is measured using data from the Silicon Pixel Detector (SPD). The primary goal is to obtain an estimator of $dN_{ch}/d\eta$ for the later study of the J/ψ production dependence on $dN_{ch}/d\eta$. Due to event-by-event fluctuations of the detector efficiency there is no unique correlation between SPD tracklets and number of charged-particles. Events with a true multiplicity, N_{ch} can be measured with different $N_{Tracklets}$. The SPD tracklets (track segments) have to be corrected to get the actual number of primary charged-particles from the reconstructed tracks. The correction method presented in this chapter of the thesis includes detector tracking efficiency and acceptance losses, track to particle conversion as well as combinatorial background. A similar procedure has been adopted as like p–Pb analysis [114] to correct the data from the SPD. We have also correct the event selection efficiency which are obtained from MC simulations. The measurements have been performed for $INEL > 0$ events, where we choose the events having at least one charged-particle within the pseudorapidity range $-1.0 < \eta < 1.0$. In order to cross-check, the obtained $dN_{ch}/d\eta$ value has been compared with true N_{ch} obtained from different MC event generators as clo-

¹“ J/ψ production as function of charged-particle multiplicity in pp collisions at $\sqrt{s} = 13$ TeV at forward rapidity” Dhananjaya Thakur and Raghunath Sahoo, ANA-734

sure tests to the adopted method. Also, the obtained $\langle dN_{ch}/d\eta \rangle$ for the MB event has been compared with [115], which has been obtained with a dedicated analysis following a different methodology using ALICE.

3.1 Event selection for multiplicity estimation

The multiplicity measurement is based on tracklets analysis reconstructed using Silicon Pixel Detector (SPD). The tracklets reconstruction is performed using the SPD vertex information as starting point. The SPD tracklets are line segments built using the SPD clusters at the two layers of the SPD detector and the vertex position. Where, The SPD vertex is estimated using the correlation between the SPD clusters information reconstructed on the two layers of the SPD. For the tracklets reconstruction, the SPD cluster information from the two layers of the detector are used along with the SPD vertex position. The SPD vertex is also reconstructed using SPD clusters. The details about the tracklets reconstruction algorithm can be found in the section 2.2.1 in the detector chapter. For the present study, we have reconstructed the number of tracklets in the $|\eta| < 1.0$ and $|SPDz_v| < 10.0$ and is used as multiplicity estimator.

3.1.1 SPD Quality Assurance selections

The multiplicity analysis is based on the tracklets reconstruction and correction, which rely on the accurate determination of the SPD vertex. A series of vertex-based cuts on the events have to be imposed to determine the accurate position of the vertex. For the current analysis, we have performed the vertex-QA for a sample of events to test the vertex-based selections.

- The first quality requirement for the events with a vertex is to have a number of contributors ($n_{contrib}$) to the SPD vertex greater than zero. For zero and negative values of the contributor, vertexer algorithms fail due to the absence of SPD clusters. Therefore, it is impossible of building suitable tracklets.

- The primary vertex of the event, z_v^p , is defined as the most accurate one. Therefore, a consistency requirement on the events should be imposed on the difference between the primary and SPD vertex position. The top left and right of Fig. 3.1(CMUL7) and Fig. 3.2(CINT7), show that the maximum events and contributors are there, when the difference between z_v^p and $SPD - z_v$ is around zero.
- Since the vertex resolution of the 1D-vertexer is worse than that of the 3D-vertexer, it is necessary to require a better resolution for events where, vertex has been reconstructed with the 1D-vertexer. The evolution of the SPD z-vertex resolution with the number of contributors can be seen in bottom left of Fig. 3.1(CMUL7) and Fig. 3.2(CINT7).
- Depending on the pseudorapidity (η) range which needs to be probed, the SPD vertex position (z_v^{SPD1}) has to be constrained to $|z_v| < z_0$ in order to keep a reasonably good acceptance of the SPD while counting the tracklets to estimate the multiplicity. The bottom right of Fig. 3.1 (CMUL7) and Fig. 3.2 (CINT7) show the SPD z-vertex distribution.

For triggers in the MUFAST cluster, only the SPD is used as readout. Consequently, unless the event also trigger simultaneously another cluster with more detector readout, e.g. the full ITS, the primary vertex is the SPD vertex and the cut on difference between the primary and SPD vertex position is meaningless. Therefore, in order to apply consistent event selection in data for CMUL7 and CINT7 events and in MC, we have to discard the cut on difference between the primary and SPD vertex position.

The same event criteria as describe in the above points have been taken into consideration when analyzing simulated events as well. In addition, only inelastic events having at least one physical primary charged-particle within $|\eta| < 1.0$ ($INEL > 0$) are selected in simulations.

¹The value of z-vertex shown in this thesis (text as well as figure) are in centimeter (cm).

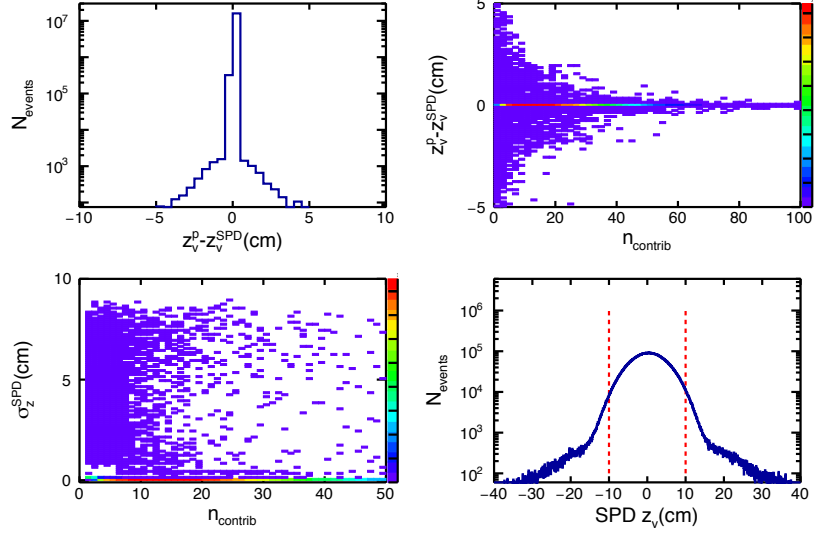


Figure 3.1. Top left: The difference of primary z-vertex and SPD z-vertex distribution for CMUL7 events. **Top right:** Difference between SPD z-vertex and primary z-vertex as function of number of contributors for CMUL7 events. **Bottom left:** SPD z-vertex resolution versus number of contributors for CMUL7 events. **Bottom right:** SPD z-vertex distribution CMUL7 events [116].

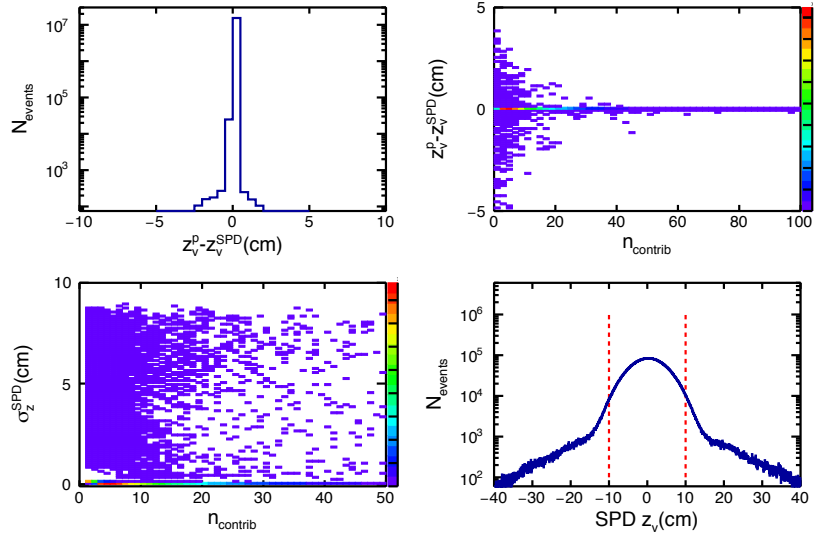


Figure 3.2. Top left: The difference of primary z-vertex and SPD z-vertex distribution for CINT7 events. **Top right:** Difference between SPD z-vertex and primary z-vertex as function of number of contributors for CINT7 events. **Bottom left:** SPD z-vertex resolution versus no.of contributors for CINT7 events. **Bottom right:** SPD z-vertex distribution for CINT7 events [116].

Following are the applied cuts on the event level for the multiplicity analysis [114, 117] for the study of forward rapidity J/ψ production as a function of multiplicity,

- Only events with a reconstructed SPD vertex are kept
- Only events which SPD vertex has $n_{contrib} > 0$ are kept
- Only events with vertex reconstructed with the SPD 1D-vertexer for which resolution is better than 0.25 cm ($\sigma_z^{SPD} < 0.25$ cm) are kept
- Only events with SPD vertex reconstructed within $|z_v| < 10.0$ cm are kept, for the current analysis.

3.1.2 Vertex QA efficiency

We have compared the number of Minimum bias number of J/ψ using vertex related cuts and without vertex related cuts to calculate vertex QA efficiency. The number of minimum-bias events and the number of J/ψ are tabulated in table. 3.1. There is a small difference of these numbers from number used for relative yield calculation, because we lost some jobs during run in grid.

Integrated No. of Events and Integrated No. of J/ψ		
-	With vertex QA cuts	W/o vertex QA cuts
N_{CINT7}	23300740	24865950
N_{CMUL7}	83831880	86739940
$N_{J/\psi}$	608521 ± 1198	626005 ± 1211

Table 3.1.

The vertex QA efficiency for J/ψ and MB(CINT7) trigger are calculated using the equations quoted below. The information about the invariant mass

reconstruction and multiplicity distribution used in vertex-QA efficiency calculation can be found in section 8.5. As we are comparing results from different analysis trains, there is a risk to bias the results by not analyzing exactly the same number of events. Therefore we normalize the number of J/ψ to the total number of events analyzed.

$$\frac{\epsilon_{vtx,QA}^{J/\psi}}{\epsilon_{vtx,QA}^{MB}} = \frac{\text{Integrated } N_{J/\psi}/N_{MB}(\text{with vertex } QA \text{ cuts})}{\text{Integrated } N_{J/\psi}/N_{MB}(\text{with out vertex } QA \text{ cuts})}$$

For the completeness, we have calculated the MB efficiency as,

$$\epsilon_{vtx,QA}^{MB} = \frac{\text{Integrated } N_{MB}(\text{with vertex } QA \text{ cuts})}{\text{Integrated } N_{MB}(\text{with out vertex } QA \text{ cuts})}$$

Using these equations, we get $\epsilon_{vtx,QA}^{J/\psi}/\epsilon_{vtx,QA}^{MB} = 1.03737 \pm 0.00288$, where $\epsilon_{vtx,QA}^{MB} = 0.93705 \pm 0.00027$.

3.1.3 Pile-up rejection

The only events are taken, those pass the physics selection `AddTaskPhysicsSelection(kFALSE,kTRUE,0,kFALSE)`, where the second argument is set to `kTRUE` to reject the pile-up events. The Fig. 3.3, shows the tracklets distribution before the physics selection and after the physics selection with the option "kTRUE". The Fig. 3.3 clearly shows the disappearance of the long tail part after the physics selection, which was due from pile up/ beam gas.

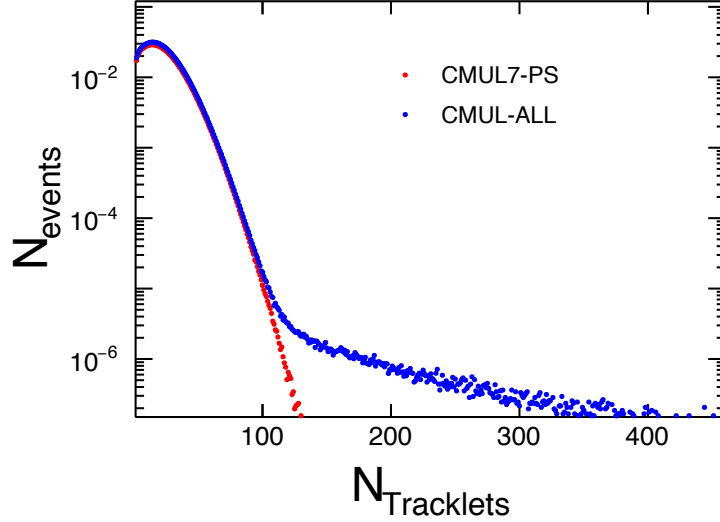


Figure 3.3. Raw tracklets distribution of all the CMUL events and physics selected CMUL events with second argument as “kTRUE” [116].

There is a non-negligible probability that one single bunch crossing may produce several separate events, so-called pile-up events. The average number of inelastic collisions per bunch crossing (μ) as a function of run numbers is shown in the Fig.3.4. The number of events in a crossing is distributed according to Poissonian distribution with the average number of collisions per beam crossing μ ,

$$P(x) = \frac{\exp(-\mu) \mu^x}{x!}. \quad (3.1)$$

The run numbers having high μ values are already discarded by the Data Processing Group (DPG). For example, in case of LHC 16h periods the maximum $\mu = 0.012$ is considered for the analysis. The maximum of μ value considered for the present analysis is tabulated in the table. 3.2 for all the analyzed periods. For the period LHC 16h, for the maximum case, the probability of having zero collision is $P(0) = \frac{\exp(-0.012) 0.012^0}{0!} = 0.988$, the probability of having one collision is $P(1) = \frac{\exp(-0.012) 0.012^1}{1!} = 0.012$. Therefore, the probability of having more than one collisions is $P(x > 1) = 1 - (P(0) + P(1)) = 7e-5$. The value $P(x > 1)$ for different periods is listed in the table. 3.2. The fraction of MB triggered events with more than one collisions would be $P(x > 1)$

/ $P(x > 0)$, where $P(x > 0) = 1 - P(0)$ is the probability to have at least one collisions (i.e. the probability to have the MB trigger fired). It can be seen from the table that the values are very less. So, at the extremum case, a very few fraction of events of the respective periods are pile up events. This is true when we consider all events integrated. However, events with pile-up will get their multiplicity biased toward higher values. Hence, while comparing to the number of events at high multiplicity the fraction of pile-up event contamination might not be so negligible. This is why we have to pay attention to this contamination in multiplicity studies. A dedicated study to pile up contamination is discussed in the section 3.3.5.

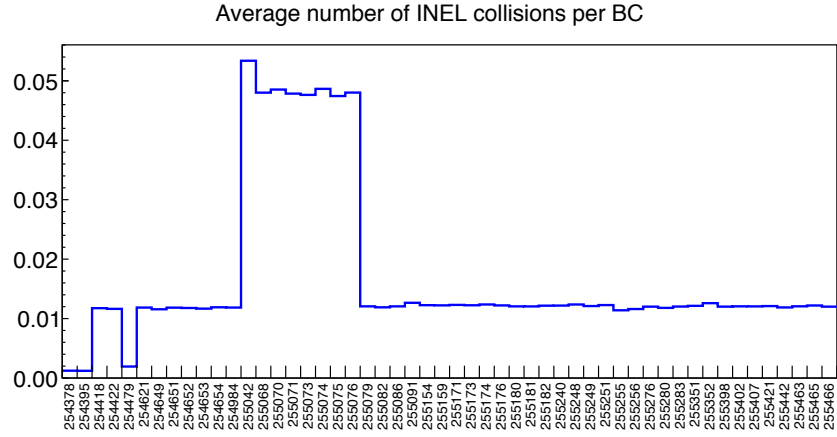


Figure 3.4. μ -value as a function of run numbers for the period, LHC 16h. For this period, run numbers around $\mu \approx 0.05$, have been discarded by PDG [116].

Maximum probability of having more than one collisions				
LHC Period	Max- μ	$P(x > 1)$	$P(x > 0)$	$P(x > 1) / P(x > 0)$
16h	≈ 0.012	7e-5	0.012	0.006
16j	≈ 0.012	7e-5	0.012	0.006
16k	≈ 0.007	2e-5	0.007	0.003
16o	≈ 0.025	3e-5	0.025	0.002
16p	≈ 0.006	1.7e-5	0.006	0.003

Table 3.2. Maximum probability of having more than one collisions for 2016 LHC periods.

3.2 SPD Status and run variation

Due to several reasons, all the SPD modules are not used in data taking and data reconstruction. For example, noisy pixels and dead pixels are removed from the data-analysis by a specific algorithm. Also, some SPD modules are not included during the data-taking. The effect of these dead regions of the detector reduces the acceptance of the SPD. The status of the SPD in terms of number and location of dead zones may vary among runs. We have checked the SPD status versus run number for all the individual run. All the analyzed run numbers of all the analyzed periods had the same SPD configuration during the runs. For example, as shown in Fig. 3.5 for 255467 run number of LHC 16h period, 68 and 156 numbers of inner and outer modules are found to be active out of 80 (85%) and 160 (97%). To have a deeper look, we have plotted the reconstructed tracklets as a function of Z_v and ϕ . It is shown in Fig.3.6. The effect of the dead zones is clearly seen on the reduced number reconstructed tracklets (tracklet density) at the regions corresponding to the dead modules of the SPD.

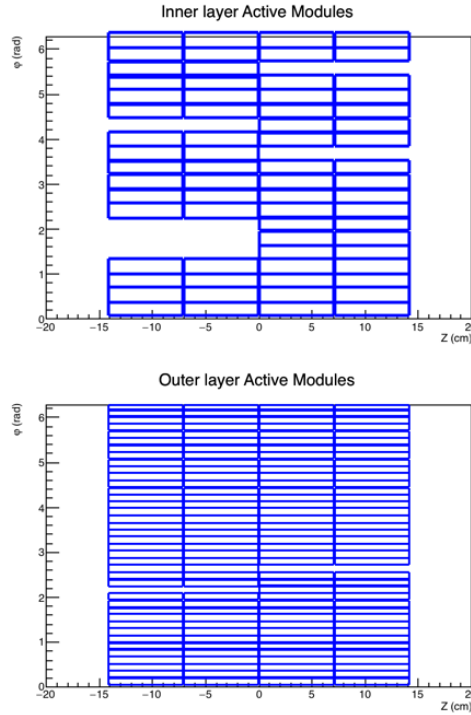


Figure 3.5. SPD Configuration for the run number 255467 for the period LHC 16h in the inner and outer module [116].

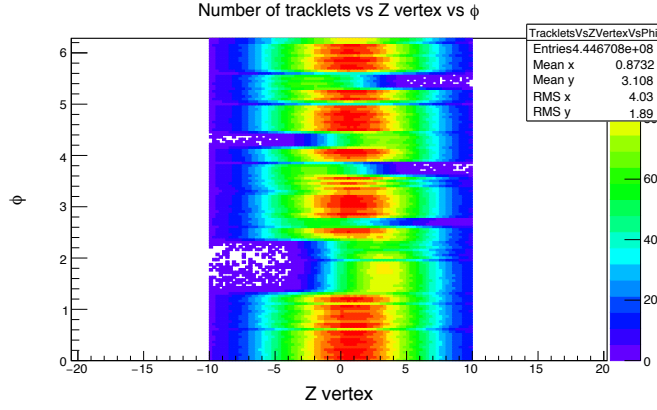


Figure 3.6. Number of reconstructed tracklets as a function z_v and ϕ for LHC 16h period [116].

3.2.1 Raw Tracklets distribution

For the current analysis, the number of tracklets reconstructed in the pseudo rapidity range $|\eta| < 1.0$ has been used as event multiplicity estimator. In order to have a reasonable SPD acceptance for this η range, the event SPD z-vertex position has to be constrained to $|z| < 10$ cm as described in the previous section. The event-averaged raw number of tracklets as a function of the interaction z-vertex, $\langle N_{trk}(z) \rangle$, and the raw tracklets distributions of MB (CINT7) as well as MUON (CMUL7) triggered events are shown in Fig.3.7 and Fig.3.8. In the absence of no inactive area and 100% efficiency, $\langle N_{trk}(z) \rangle$ as a function of z-vertex should be flat in the SPD acceptance range of $|\eta| < 1.0$. For the $|\eta| < 1.0$ multiplicity estimator, the SPD acceptance is not complete. So, if the full SPD would work at 100% efficiency, the $\langle N_{Trk} \rangle$ should be flat around $|Z_{vtx}| < 6.0$ cm region (corresponds to $|\eta| < 1.0$ acceptance) and would drop towards the edges (-10 and +10 cm) due to acceptance effect. But, It is not the case here and can be clearly seen from the Fig.3.7. Due to the SPD inactive modules and inefficiencies, the measured event-averaged number of tracklets as a function of the event interaction vertex z-coordinate is not flat. Therefore, the acceptance and efficiency corrections need to be done for SPD for the multiplicity measurement. For the current analysis, we have adopted the data driven method to correct efficiency and acceptance [114]. This will be

discussed in the next section.

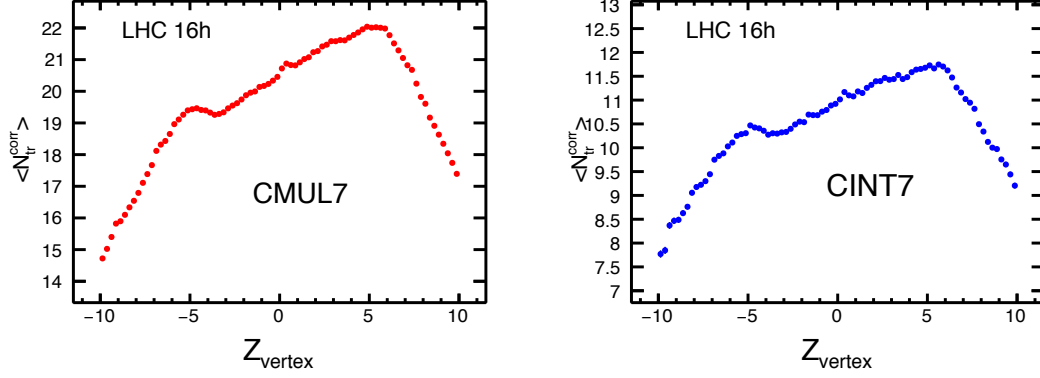


Figure 3.7. Raw event-averaged number of tracklets for LHC 16h period for CMUL7 (Left) and CINT7 (Right) triggers [116].

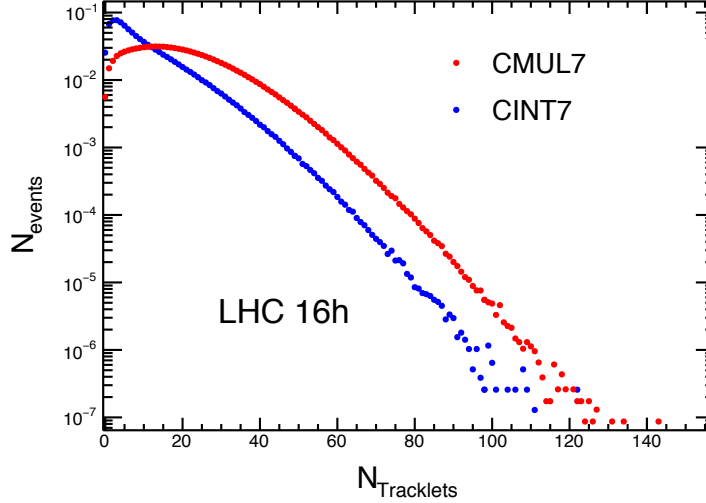


Figure 3.8. Distribution of raw tracklets for LHC 16h period for CMUL7 and CINT7 triggers [116].

3.2.2 Multiplicity correction by data-driven method

The basis of the data-driven correction is to equalize the SPD efficiency along the z-vertex direction. It uses the mean raw number of reconstructed SPD tracklets as a function of the interaction z-vertex, $\langle N_{Trk}(z_v) \rangle$. The method corrects event multiplicities by the efficiency loss of the detector with respect to a reference value. Fig. 3.11 shows the event-averaged number of charged particles, reconstructed number of tracklets ($\langle N_{Trk} \rangle$) and corrected number of

tracklets ($\langle N_{Trk}^{corr} \rangle$) tracklets in $|\eta| < 1.0$ as a function of the event interaction z-vertex coordinate (z_v) for pp MC samples (detailed about this will be discussed in section. 3.3). As discussed in the previous section, as a result of the SPD inefficiencies and acceptance losses due to inactive modules during the data-taking, $\langle N_{Trk}(z) \rangle$ is smaller than the generated and is not flat as observed for $\langle N_{ch}(z) \rangle$. To correct for the z-vertex dependence of the reconstructed number of tracklets, we have performed the *acceptance $\times$ efficiency* correction using the data driven method as adopted for these kind of analysis [114] [118, 119]. It uses no specific MC production and correction is done from data itself. The correction procedure uses the measured $\langle N_{Trk}(z_v) \rangle$ distribution itself and is based on choosing a $\langle N_{Trk}(z_v^0) \rangle$ value as a reference. Then the number of tracklets for each event reconstructed at a given z-vertex position, $N_{Trk}(z_v)$, is corrected by the average fraction of missing tracklets at the interaction vertex z respect to the reference value, by the formula:

$$\Delta N = \frac{\langle N_{trk} \rangle(z_v^0) - \langle N_{trk} \rangle(z_v)}{\langle N_{trk} \rangle(z_v^0)} \quad (3.2)$$

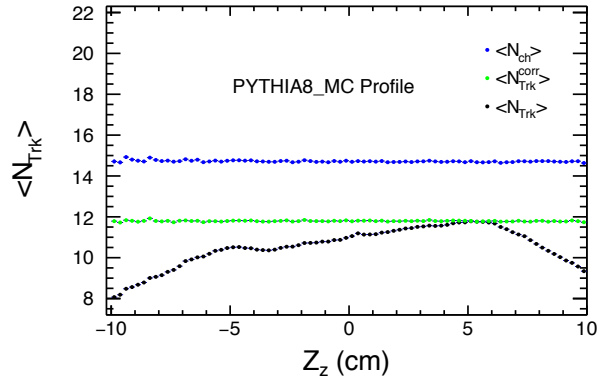


Figure 3.9. Generated event-averaged number of charged particles, reconstructed event-averaged number of tracklets and corrected event-averaged number of tracklets. Here, for the calculation of corrected event-averaged number of tracklets, MC Profile with the reference ($\langle N_{trk} \rangle(z_v^0)$) from the corresponding profile has been used [116].

Then using ΔN as the mean of the Poisson (Binomial) distribution for $\Delta N > 0$ ($\Delta N < 0$), we have generated the random numbers (ΔN_{rand}) and the corrected number of tracklets is calculated as

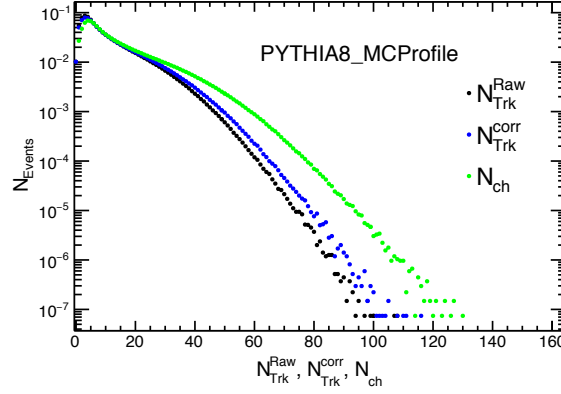


Figure 3.10. Distribution of generated number of charged particles, reconstructed number of tracklets and corrected number of tracklets [116].

$$N_{\text{trk}}^{\text{corr}}(z_v) = N_{\text{trk}}(z_v) + \Delta N_{\text{rand}} \quad (3.3)$$

The choice of the Poissonian/Binomial distribution for the missing tracklets is verified in [114, 120, 121]. If $\langle N_{\text{trk}} \rangle(z_v^0)$ is greater than $\langle N_{\text{trk}} \rangle(z_v)$, then ΔN_{rand} is positive and negative in the opposite case. In this way we can add/remove the missing/excess tracklets in a z-vertex position with respect to the reference value.

Choice of reference value

The discussed Poissonian smearing method is able to account for dispersion differences with respect to the reference value. With the proper choice of the reference in the correction, this method allows to get a uniform dispersion along z-vertex. Any choice of the reference value, $\langle N_{\text{Trk}}^{\text{corr}} \rangle(z_0)$, leads to a flat $\langle N_{\text{Trk}}^{\text{corr}} \rangle(z_v)$ distribution. As shown in the illustrative Fig. 3.11, an excess or deficit of the $\langle N_{\text{Trk}} \rangle$ with respect to the reference value will be added/subtracted and finally we will land with a flat distribution of $\langle N_{\text{Trk}} \rangle$ as a function of z_{vtx} . Here, we need to take the proper distribution (mainly Poissonian/Binomial distributions are used) for the random number generation. Each choice of reference value has its pros and cons. The detailed about the advantages and disadvantages of the choice of reference has been discussed in Ref. [114]. The corrected event

multiplicity obtained by this method is not the actual charged particle multiplicity, since it has been corrected by the efficiency loss with respect to the reference value ($\langle N_{trk} \rangle(z_v^0)$), where the SPD efficiency is not necessarily 100%. Therefore, it is needed to take into account the efficiency loss and effects from charged secondaries (e.g strange particle decays, photon conversion etc.) at z_v^0 , also tracklet-to-particle correction. This will be discussed in the subsequent section.



Figure 3.11. An illustrative figure showing equalization of N_{trk} with the choice of any reference. The figure shown is inspired from the presentation [120].

Choice of the profile

The choice of profile for the correction of mean tracklets is a tricky thing. It should be chosen properly, otherwise it can bias the multiplicity distribution. For the current analysis, we analyze the CMUL7 and CINT7 events. The profile of $\langle N_{Trk} \rangle(z_v)$ is shown in Fig. 3.12 for CINT7 as well as CMUL7. It can be seen from the figure that both the profiles show the similar shape. This observation is obvious, because SPD status is similar during the runs for CMUL7 as well as CINT7. To study the difference, we have plotted the ratio plot of CMUL7 to CINT7 $\langle N_{Trk} \rangle(z_v)$ profile as shown in Fig. 8.6 and it seems to be almost flat with a little fluctuation. The difference between the profile of CMUL7 and CINT7 events, most probably is due to bias of the dimuon trigger. A possible explanation could be that due to the z-vertex dependence of the decay probability of pions and kaons into muons before the absorber of MUON Spectrometer. This in turn affects the dimuon trigger.

Thereafter, we have tried to study the variation of $\langle N_{Trk} \rangle(z_v)$ profile from

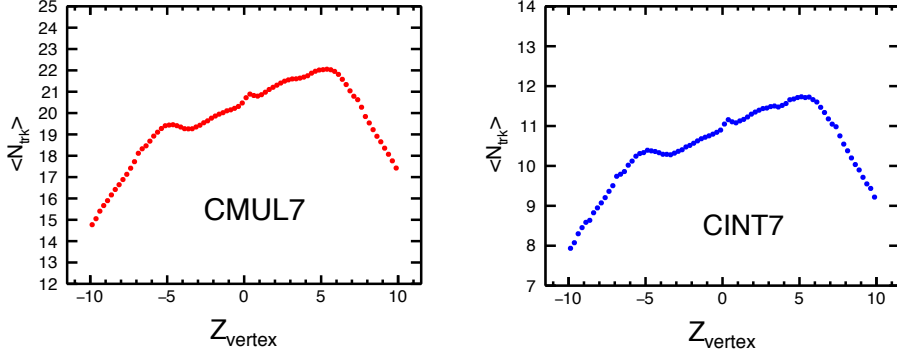


Figure 3.12. $\langle N_{Trk} \rangle$ vs. z_v profile of CINT7 and CMUL7 for the 16h+16j+16k+16o+16p data set [116].

period to period. As the SPD status is same for all the run numbers and also for all the periods, the $\langle N_{Trk} \rangle(z_v)$ vs. z_{vtx} should not vary from period to period. It can be seen from the Fig. 3.14 that the $\langle N_{Trk} \rangle(z_v)$ profile is almost flat for CMUL events from period to period. The little fluctuation may be due to the different beam gas contamination of the di-muon trigger, which depends on the beam condition. To have an idea regarding the beam gas contamination, we have regrouped the run numbers based on their beam condition and studied its effect. The detailed about the study based on beam gas condition can be found in the appendix section 8.4. We have not found much variation across beam condition as well. This reveals that the beam contamination may have a little effect but it does not have substantial effect on the tracklets equalization. Therefore, we proceed for equalization of the $\langle N_{Trk} \rangle$ on period by period basis.

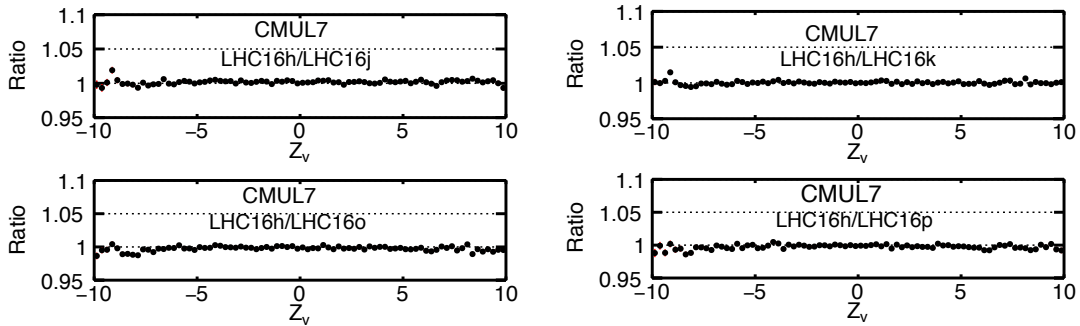


Figure 3.14. Period to period variation of CMUL7, $\langle N_{Trk} \rangle$ vs. z_v profile [116].

The ultimate aim of our correction is to equalize the $\langle N_{Trk} \rangle$ distribution versus z-vertex to make sure we select the same class of multiplicity independent

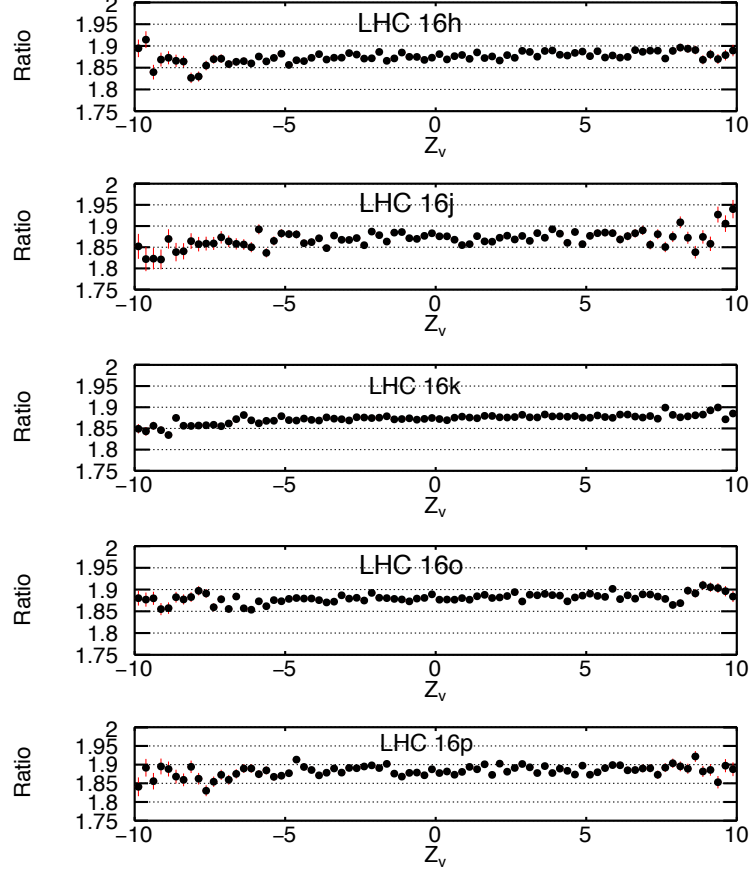


Figure 3.13. Ratio of CMUL7 to CINT7, $\langle N_{Trk} \rangle$ vs. z_v profile for all the periods (16h,16j,16k,16o,16p) [116].

of z_v . It would have been better to use CMUL profile to correct CINT as well as CMUL events, as it has higher statistics and hence less fluctuations, provided CINT and CMUL profile are identical. But, here it is not the case, may be due to bias in di-muon trigger. On the other hand, the ratio of CINT profile between the periods is flat, therefore it is possible to use combine profile of all the periods (16h + 16j + 16k + 16o + 16p) to maximize the statistics and use for the correction. To check the feasibility, we have plotted the ratio between the overall profile and one obtains in each period. It can be seen from the Fig. 3.15 that the ratio is almost flat around one.

From the above studies, we conclude that combine $\langle N_{Trk} \rangle(z_v)$ profile (16h + 16j + 16k + 16o + 16p) should be used with the maximum of it as reference ($\langle N_{Trk} \rangle(z_v^0)$) for the correction. For the current analysis, the reference value is $\langle N_{Trk} \rangle(z_v^0) = 11.74$: the maximum of the $\langle N_{Trk} \rangle(z_v)$ versus z_v profile. However,

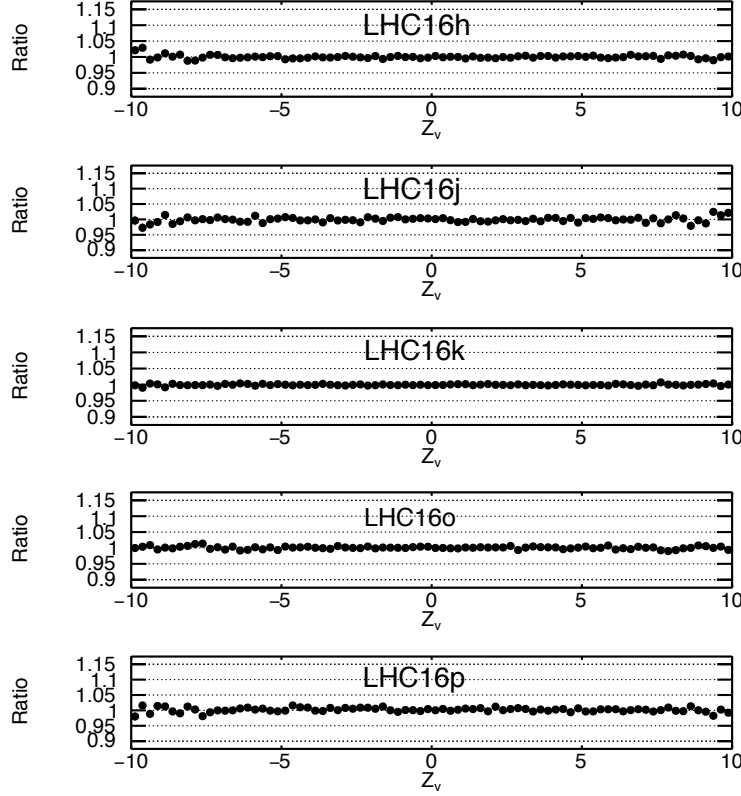


Figure 3.15. Ratio of overall CINT7 (16h + 16j + 16k + 16o + 16p) to CINT7, $\langle N_{Trk} \rangle$ vs. z_v profile of respective periods [116].

we have tested how much the other choice of reference value is affecting the final results which will be discussed in the section. 3.2.3.

Corrected tracklets distribution

As discussed in the previous section, we have used the integrated CINT7 profile with the maximum of it as the reference value. The tracklets correction is performed for all the periods separately using the single integrated CINT7 profile with the same reference value for all the periods. From Figs. 3.17, 3.16 and Figs. 3.18, it can be clearly seen that $\langle N_{Trk} \rangle(z_v)$ is flat around its maximum value for CINT7 events. For CMUL7 events, it is not perfectly flat, as expected, for the same reasons as explained before. There is small statistical fluctuation around the lower and higher z_v values. After combining all the periods (LHC 16h + 16j + 16k + 16o + 16p), $\langle N_{Trk} \rangle(z_v)$ distribution gives a flat distribution with the disappearance of any fluctuation and this can be

seen from the Fig. 3.19. After the correction, we have plotted the corrected tracklet distribution along with the un-corrected tracklets distribution in the same panel, as shown in the Fig. 3.20.

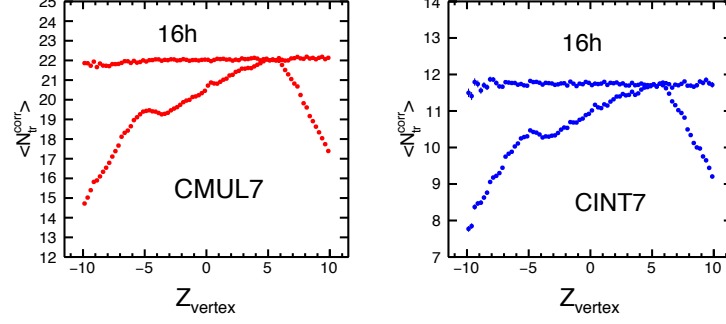


Figure 3.16. $\langle N_{Trk} \rangle$ vs. z_v profile of LHC 16h for CINT7 and CMUL7. In both CMUL7 and CINT7, for the calculation of $\langle N_{Trk}^{corr} \rangle$, integrated CINT7 profile (16h + 16j + 16k + 16o + 16p) with the reference($\langle N_{Trk} \rangle(z_v^0)$) from the corresponding profile has been used [116].

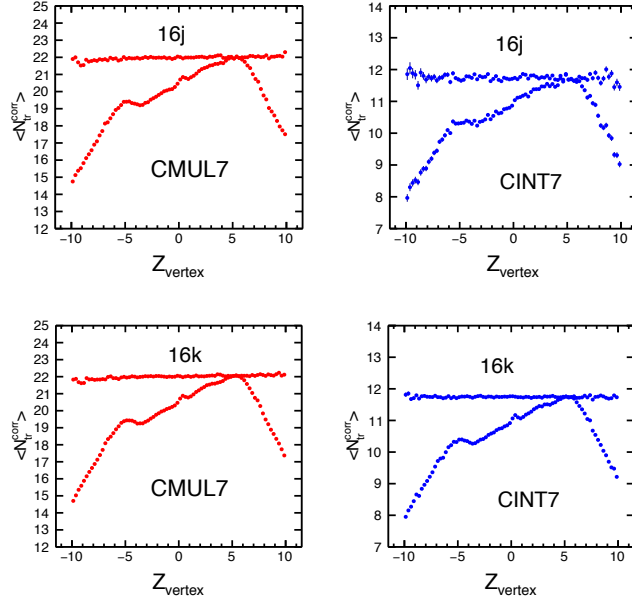


Figure 3.17. $\langle N_{Trk} \rangle$ vs. z_v TProfile of LHC 16j(1st, 2nd) and LHC 16k(3rd, 4th), for CINT7 and CMUL7. In both CMUL7 and CINT7, for the calculation of $\langle N_{Trk}^{corr} \rangle$, integrated CINT7 Profile(16h + 16j + 16k + 16o + 16p) with the reference($\langle N_{Trk} \rangle(z_v^0)$) from the corresponding profile has been used [116].

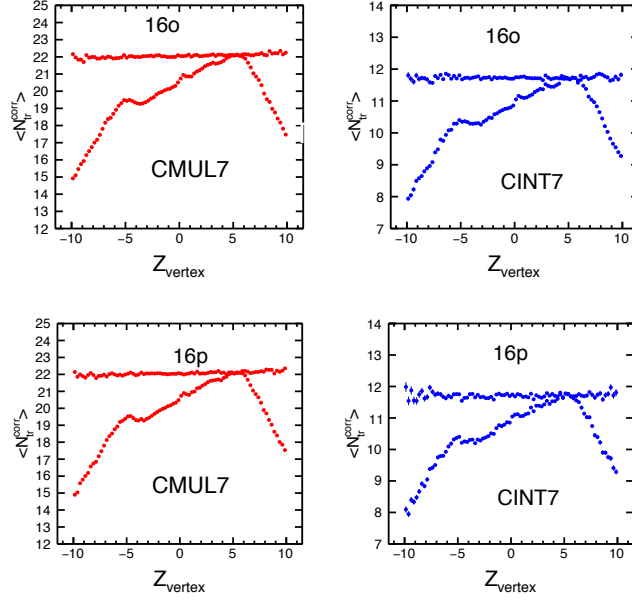


Figure 3.18. $\langle N_{Trk} \rangle$ vs. z_v profile of LHC 16o (1st, 2nd) and LHC 16p(3rd, 4th), for CINT7 and CMUL7. In both CMUL7 and CINT7, for the calculation of $\langle N_{Trk}^{corr} \rangle$, integrated CINT7 profile(16h + 16j + 16k + 16o + 16p) with the reference($\langle N_{Trk} \rangle(z_v^0)$) from the corresponding profile has been used [116].

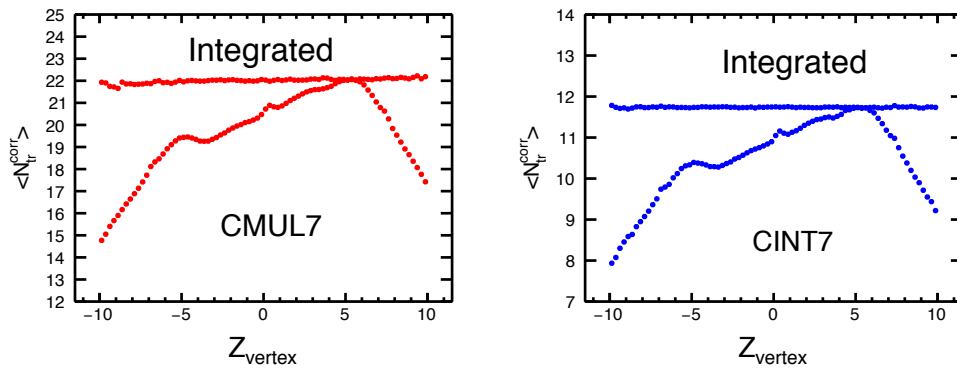


Figure 3.19. $\langle N_{Trk} \rangle$ vs. z_v profile of Integrated period (LHC 16h+16j+16k+16o+16p) for CINT7 and CMUL7. In both CMUL7 and CINT7, for the calculation of $\langle N_{Trk}^{corr} \rangle$, integrated CINT7 profile(16h + 16j + 16k + 16o + 16p) with the reference($\langle N_{Trk} \rangle(z_v^0)$) from the corresponding profile has been used [116].

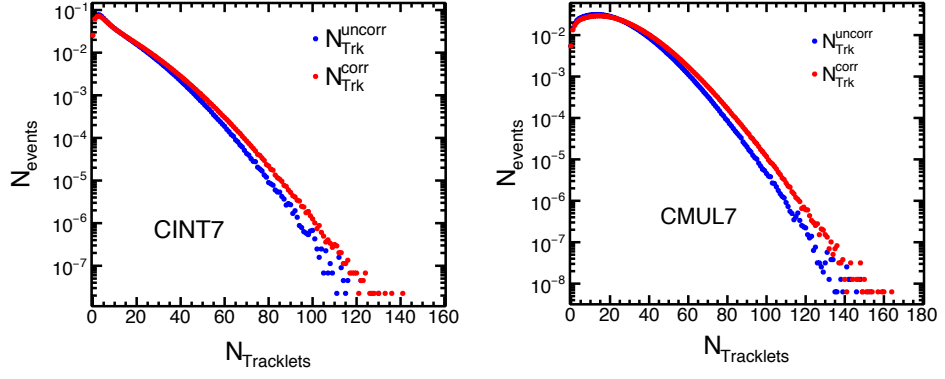


Figure 3.20. Tracklets distribution of CINT7 and CMUL7 for the integrated periods (LHC 16h+16j+16k+16o+16p) [116].

We have performed the consistency check to test the Z_{vtx} equalization of $\langle N_{Trk} \rangle$. After the correction, as $\langle N_{Trk} \rangle$ should be independent of Z_{vtx} , so the corrected tracklet distribution should be identical irrespective of the Z_{vtx} ranges. We have done this test taking five different Z_{vtx} intervals $(-10.0 \text{ to } 10.0)$, $(-10.0 \text{ to } -5.0)$, $(-5.0 \text{ to } 0.0)$, $(0.0 \text{ to } 5.0)$, $(5.0 \text{ to } 10.0)$. This can be seen from the Fig.3.22 that the uncorrected tracklets do not equalize along different Z_{vtx} intervals, whereas after the corrections, the corrected tracklet distributions are identical in different Z_{vtx} intervals. However, we have seen a little fluctuation for $(-10 \text{ to } -5.0)$ because of lack of statistics. The equalization along Z_{vtx} interval will be taken care in the systematic uncertainty of $\langle N_{ch} \rangle$ calculation, where we have taken it as a sources of systematic uncertainty.

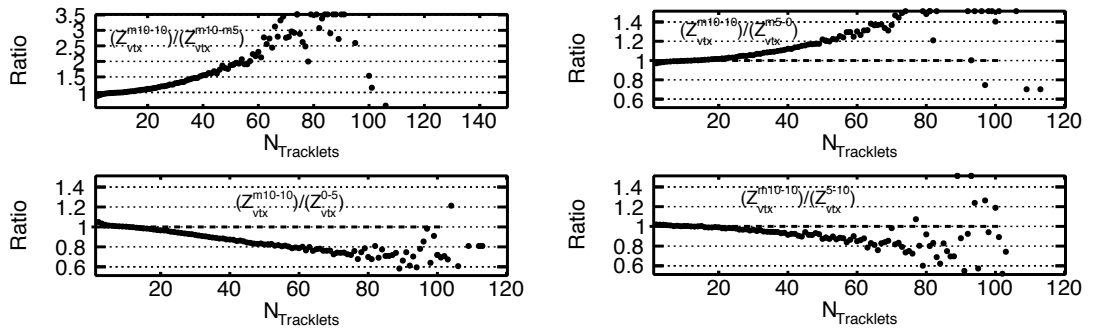


Figure 3.21. Ratio of un-corrected tracklet distributions in different Z_{vtx} intervals with $-10.0 < Z_{vtx} < 10.0$ [116].

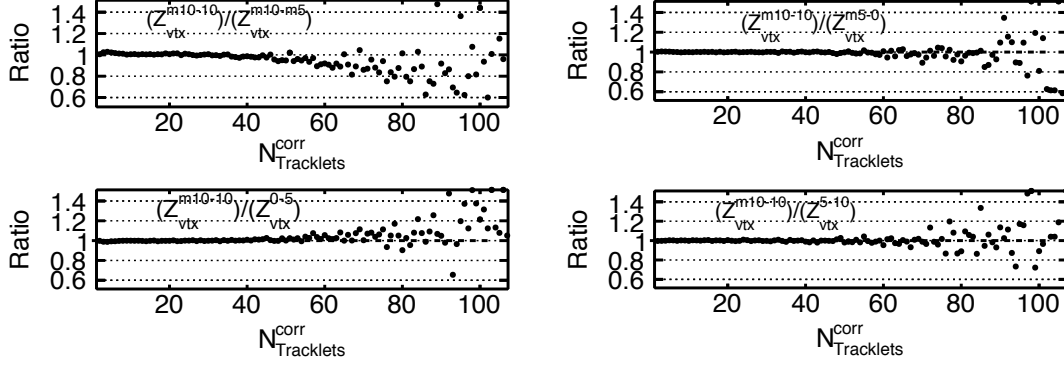


Figure 3.22. Ratio of corrected tracklet distributions in different Z_{vtx} intervals with $-10.0 < Z_{vtx} < 10.0$ [116].

3.2.3 Tracklets correction using other choices of reference (Minimum)

We have tried to correct the tracklet distributions using other choices of reference values. The best way to correct $\langle N_{Trk} \rangle$ vs. z_v distribution is by using its extremum points. So, it is either by maximum or minimum of $\langle N_{Trk} \rangle$ vs. z_v . We have already performed the correction of tracklets using maximum as reference, as described in the above sections. The other way is to repeat the analysis taking minimum as reference. We have followed all the steps as for maximum and performed the correction taking minimum as reference. It is to be noted that we have used the Poissonian random number to correct the $\langle N_{Trk} \rangle$ [120]. The $\langle N_{Trk} \rangle$ correction taking minimum as well as maximum is shown in the Fig.3.23 for the integrated sample of CMUL7 and CINT7 events. After the corrections, we have plotted the raw as well as corrected tracklets distribution taking both the reference values. This is shown in Fig. 3.24. It can be shown from the figure that using maximum as reference, we are reaching higher multiplicity value as compared to minimum. The obtained corrected tracklet distribution, N_{Trk}^{corr} , can not be used as final multiplicity value. We have performed the correlation of N_{Trk}^{corr} versus physical primary N_{ch} to obtain the true charged-particle which is discussed in section. 3.3.1. Both the choices of reference value will lead to almost same reach of charged-particle multiplicity,

although the N_{Trk}^{corr} value in minimum case is less as compared to maximum. The signal extraction and relative yield calculations have been performed using maximum as well as minimum as reference to see if there is any difference in the final results. The effects of choices of the reference values on the final results have been discussed in the section. ??.

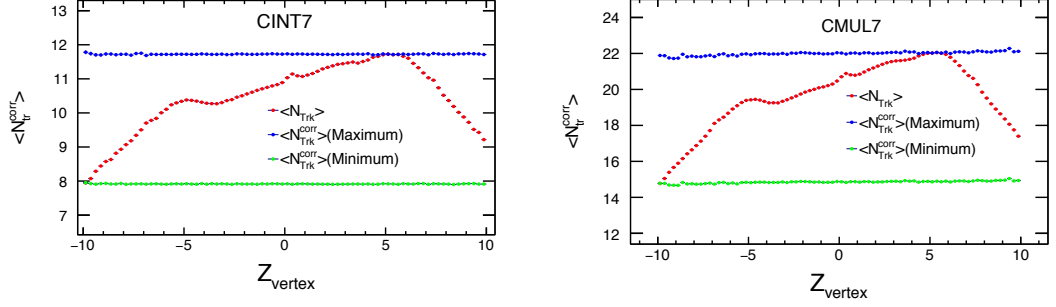


Figure 3.23. $\langle N_{Trk} \rangle$ vs. z_v for integrated sample(16h+16j+16k+16o) taking minimum and maximum as reference, for CINT7 and CMUL7 [116].

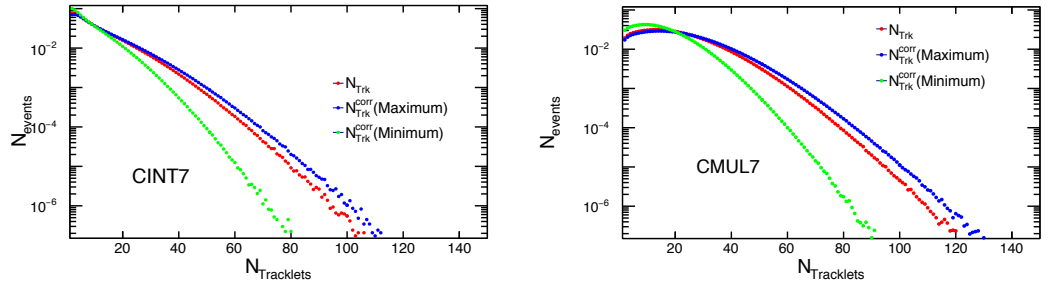


Figure 3.24. Raw and corrected tracklets distribution for integrated sam-ple(16h+16j+16k+16o+16p) taking minimum and maximum as reference, for CINT7 and CMUL7 [116].

Note:: Using Poissonian distribution when normalizing to the minimum might lead to some events with a negative number of N_{Trk}^{corr} . This is why, it is better to use a binomial distribution but will not lead to any significant difference. So, for the testing purpose we have used Poissonian distribution in both the cases. However, for the final results maximum as reference has been used.

3.3 Monte Carlo Analysis

As discussed in the previous section, the effects of the efficiency variations and resolution with the z-vertex position have been corrected using a data driven method. In order to obtain the true N_{ch} value, we need to correct by the efficiency loss at the reference (z_v^0) and by the other tracklet-to-particle corrections. For this, we need to know the correlation of the event-averaged number of corrected tracklets in a certain multiplicity range with the number of primary charged particles. This correction can be obtained from a MC analysis, computing the correlation between $N_{\text{trk}}^{\text{corr}}$ and the generated $N_{\text{ch}}^{\text{gen}}$. In general, the differences on the charged-particle distribution from tracklet distribution, detector effect on the data have been studied using Monte Carlo production. For this purpose, we have used the general purpose MC production which uses PYTHIA8 (Monash 2013 tune) and EPOS. The table 3.3 enlists the MC data periods used for the current analysis.

MC Production periods	
MC	Anchored to
LHC17f5	LHC 16h (PYTHIA8)
LHC17e5	LHC 16j (PYTHIA8)
LHC17d20a1	LHC 16k (PYTHIA8)
LHC17d16	LHC 16o (PYTHIA8)
LHC17d18	LHC 16p (PYTHIA8)
LHC17d20b1	LHC 16k (EPOSLHC)

Table 3.3. MC Production periods anchored to data.

Event selection for the MC Analysis:

The selected events are required to pass physics selection `AddTaskPhysicsSelection (kTRUE,kTRUE,0,kFALSE)` and have the same event selection criteria as data. We have listed below the event selection applied to MC,

- Physics selection applied(`kINT7`)
- At least one physical-primary charged-particle in $|\eta| < 1.0$ (`INEL > 0`)
- $\sigma_{Z_v^{SPD}} < 0.25$ cm
- $N_{contributors} > 0$.
- $Z_v^{SPD} < 10.0$ cm

First, to see how the data describing the MC, we have compared the basic distribution like z_{vertex} , tracklets and $\langle N_{Trk} \rangle$ vs. z_{Vertex} between data and MC. The comparison results of MC and data are shown in Fig. 3.25 and Fig. 3.26.

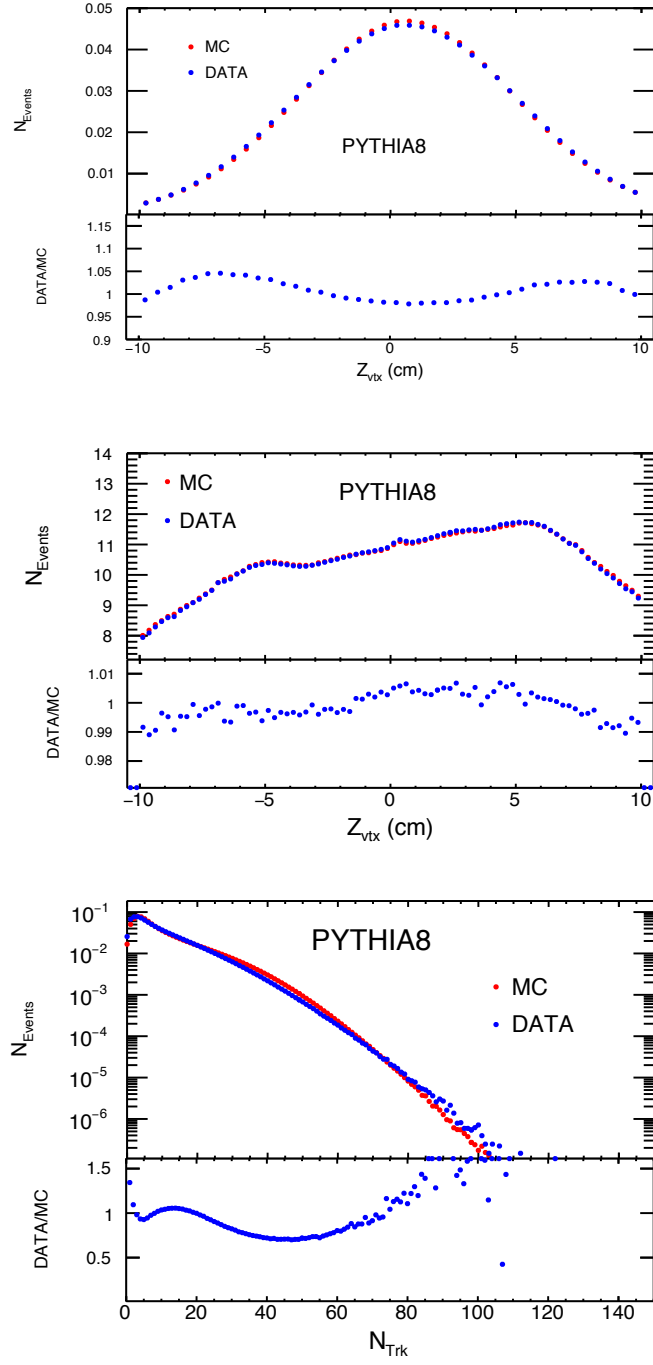


Figure 3.25. Comparison of data and PYTHIA8 for vertex (Top), $\langle N_{Trk} \rangle$ Vs. Z_{Vertex} distribution (Middle) and tracklet distribution (Bottom) [116].

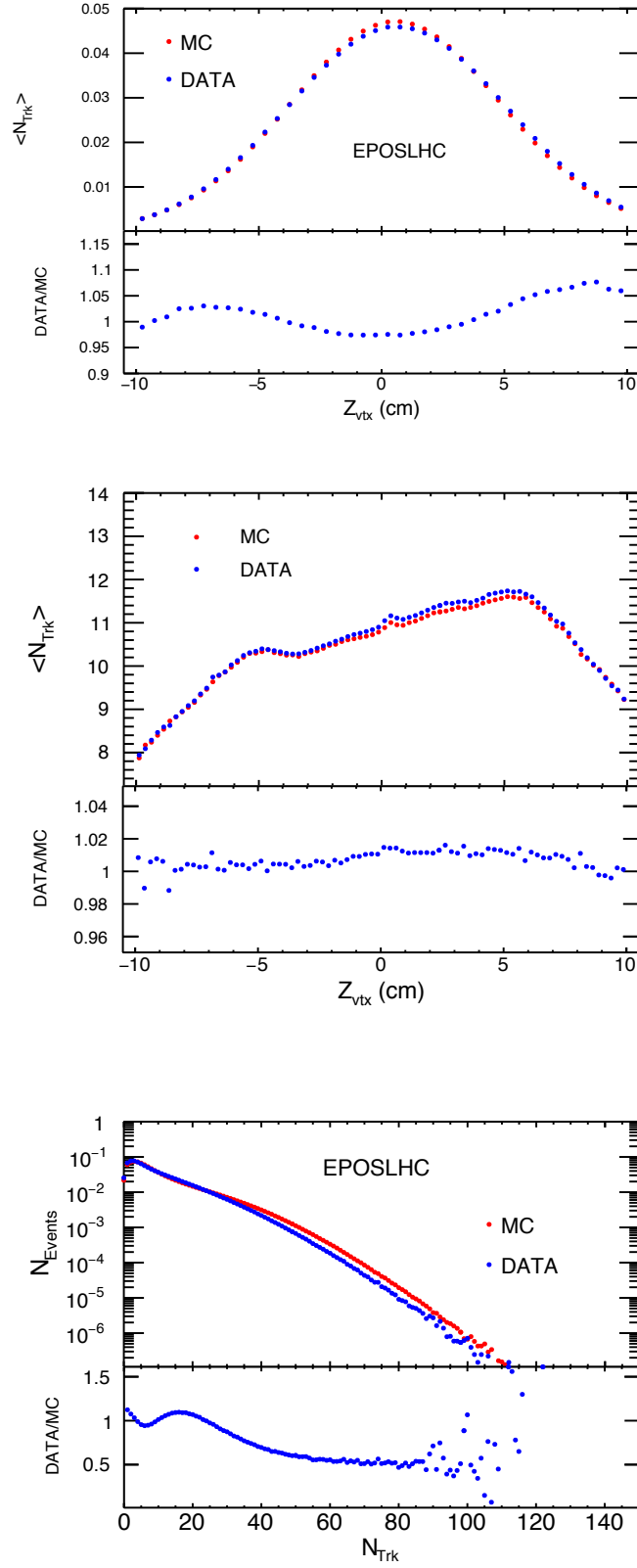


Figure 3.26. Comparison of data and EPOS LHC for vertex (Top), $\langle N_{Trk} \rangle$ Vs. Z_{Vertex} distribution (Middle) and tracklets (Bottom) [116].

Using MC production enlisted in table. 3.3 which are anchored to the LHC periods used for the analysis, we have followed the data driven procedure to correct the reconstructed tracklets like data. For the correction, the same profile (Integrated CINT7 profile) and reference value (11.74) are used, which are used in data. This allows us to estimate N_{Trk}^{corr} from N_{Trk} in the same manner as in data. To take into account the difference in data and MC, we have used profile from MC and repeated the procedure which will be discussed in systematic section. We have corrected the mean tracklet distribution of each period separately. The $\langle N_{Trk} \rangle$, $\langle N_{Trk}^{corr} \rangle$ along with the $\langle N_{ch} \rangle$ distribution is shown in Fig. 3.28. There might be some small non flatness of the $\langle N_{Trk} \rangle$ equalization, which is due to the fact that the profile used is from data, and that does not exactly match with the profile of simulation. However, this is well within systematics and should not impact the results, as we are considering different profiles (data profile and MC profile) as one of our sources of systematic uncertainty. The multiplicity distribution of each period equalize very well with the other. This can be seen from Fig. 3.27. We have added all the periods to calculate the N_{Trk}^{corr} to N_{ch} correlation factor which will take care of the efficiency loss at the reference point (z_v^0), with respect to which the correction has been performed. The correlation study also takes care of tracklet-to-particle correction.

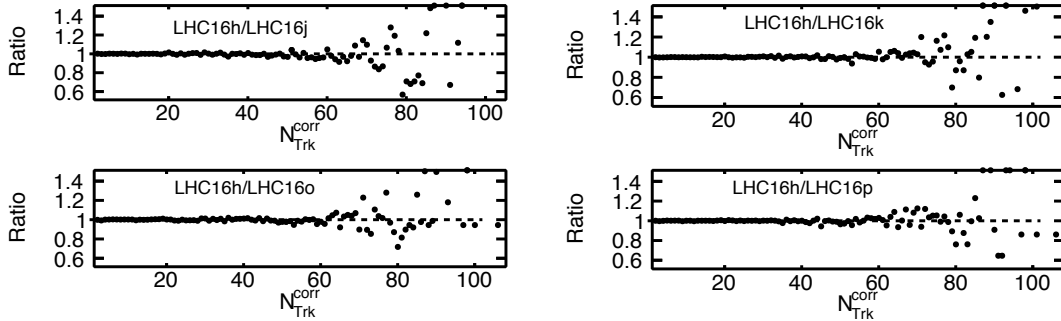


Figure 3.27. Multiplicity equalization along the MC (PYTHIA8) periods anchored to analyzed LHC periods. The results shown here uses data profile and Maximum of $\langle N_{Trk}(z_v) \rangle$ as reference value for the reconstructed SPD tracklets correction [116].

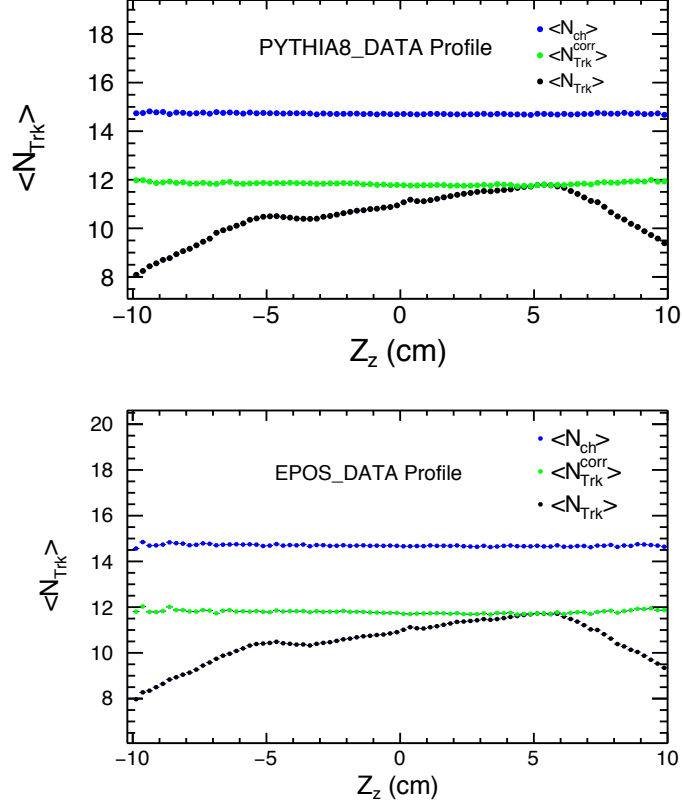


Figure 3.28. Raw $\langle N_{Trk} \rangle$, corrected $\langle N_{Trk} \rangle$ and $\langle N_{ch}^{gen} \rangle$ as a function of z_v for PYTHIA8 (for LHC16h+16j+16k+16o) and EPOS (LHC 16k) [116].

3.3.1 N_{Trk}^{corr} to N_{ch} correlation study

The corrected tracklets (N_{Trk}^{corr}) obtained in the data driven method is not the actual N_{ch} value. As discussed in the previous section, there is efficiency loss at the point z_0 and other track-to-particle corrections needed to be done to get the actual charged-particle value. The effect of efficiency variation and resolution variation along the z-vertex is already corrected and therefore, the $\langle N_{Trk} \rangle$ is flat along the z-vertex. In the absence of detectors, for primary charged particles, $\langle N_{ch} \rangle$ is expected to be constant along the z-vertex and can be seen from Fig. 3.28. The exact N_{ch} value can be obtained by the correlation between corrected tracklets (N_{Trk}^{corr}) and primary charged particle (N_{ch}). The correction factor for integrated multiplicity is $\alpha = N_{ch}^{gen} / N_{Trk}^{corr}$ and this can be obtained by a linear fit to N_{ch}^{gen} vs. N_{Trk}^{corr} distribution. The α factor takes care

of the efficiency loss at z_0 and track-to-particle corrections. As each tracklet corresponds to a charged-particle, in principle, N_{ch} to N_{Trk}^{corr} correlation should be perfectly linear. But, from the Fig. 3.28, it can be seen that the correlation is not perfectly linear, there is a slight deviation from linearity towards high multiplicity. Therefore to obtain the actual charged-particles corresponding to N_{Trk}^{corr} , we have adopted two methods:

- (A) **Method1:** By linear fit [$f(x) = \alpha \times x$] to N_{ch} vs. N_{Trk}^{corr} correlation, with properly taking care of non-linearity, by fitting the correlation to each multiplicity interval separately.
- (B) **Method2:** Direct evaluation of N_{ch} using an add-hoc polynomial, with the weighting of events from data.

To account for the dependence of N_{Trk}^{corr} to N_{ch} correlation on the choice of reference value, the study has been performed for two choices of references: maximum and minimum i.e two extremities. We have discussed in detailed about Method1 3.3.1 and Method2 3.3.1 in separate sections.

Method1

As we are interested in multiplicity dependence study of J/ψ production, the starting point of this analysis is MB N_{Trk}^{corr} . We have divided the MB N_{Trk}^{corr} in different intervals keeping in mind that, there should be sufficient number of J/ψ for the current study as shown in Fig.3.29. If the event averaged corrected number of tracklets in i^{th} multiplicity bin is $\langle N_{Trk}^{corr} \rangle_i$, then the corresponding value of the event-averaged charged-particle multiplicity density in that multiplicity bin can be computed as follows:

$$\langle dN_{ch}/d\eta \rangle_i = \frac{\langle N_{Trk}^{corr} \rangle_i \times \alpha_i}{\Delta\eta} \quad (3.4)$$

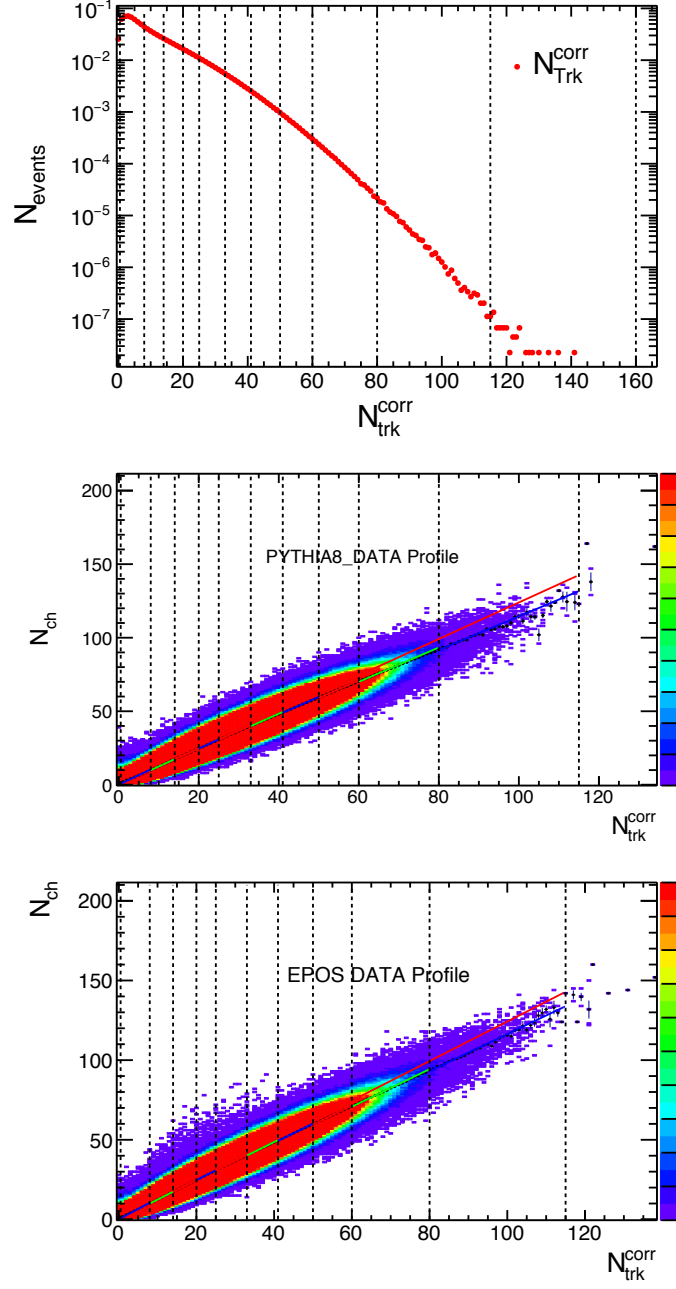


Figure 3.29. Top: Corrected tracklets distribution in MC combining all the periods mentioned in table. 3.3. Vertical lines delimit the multiplicity bins chosen for the analysis. **Middle and Bottom:** $N_{\text{Trk}}^{\text{corr}}$ to N_{ch} correlation plot using data profile for the correction for PYHTIA8 and EPOS, where vertical lines represents the multiplicity bins chosen for the analysis. The fits are used to get the global correction (red line) and the bin-by-bin ones [116].

As the tracklets are selected in the interval: $-1.0 < \eta < 1.0$, therefore $\Delta\eta = 2.0$. The correction factor in each multiplicity interval (α_i) is obtained

by fitting $N_{trk}^{corr} - N_{ch}$ correlation plot by linear function in each multiplicity bin. In Fig.3.29, the different color lines represent the fitting results in each multiplicity intervals. The value of α_i corresponds to each multiplicity interval is tabulated in table. 3.12.

To get the relative charged-particle density $dN_{ch}/d\eta/\langle dN_{ch}/d\eta \rangle$, the bin $\langle dN_{ch}/d\eta \rangle_i$ has to be divided by event-averaged charged particle multiplicity. Therefore, the relative multiplicity in i^{th} bin will be simply:

$$\left(\frac{dN_{ch}/d\eta}{\langle dN_{ch}/d\eta \rangle} \right)_i = \frac{\langle N_{Trk}^{corr} \rangle_i}{\langle N_{Trk}^{corr} \rangle} \quad (3.5)$$

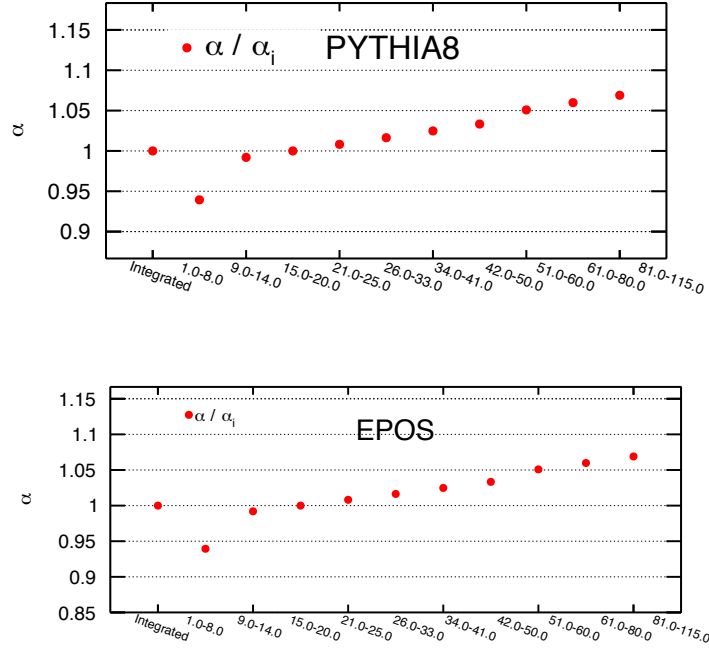


Figure 3.30. Deviation of global alpha (α) from the bin-by-bin alpha (α_i) value using PYTHIA8 and EPOS [116].

For the ideal case where the charged particle vary linearly with corrected tracklets, $\alpha_i = \alpha$ and this implies that missing efficiency and track-to-particle effect is independent of multiplicity. But, it is not the case. It can be seen from Fig.3.29 that the red line diverges from the black points towards the higher multiplicities. To have a clear view, we have studied the ratio of α , which is

obtained by fitting integrated $N_{Trk}^{corr} - N_h$ correlation, with the α_i . The α to α_i ratio has been plotted in the Fig.3.30. It can be seen from the figure that, except some multiplicity bins in the middle, it is mostly deviating from 1. We found a maximum deviation of 6.06 %, and is for the first multiplicity bin ($N_{ch} = 1 - 8$). This is the maximum uncertainty from non-linearity.

The current analysis uses $p + p$ data and $INEL > 0$ events, which takes that events which contains at least one charged-particle ($N_{ch} > 0$). In the Ref. [115], a dedicated analysis is performed to calculate $\langle dN_{ch}/d\eta \rangle$ for $INEL > 0$. The value is $\langle dN_{ch}/d\eta \rangle = 7.02 \pm 0.11$ for $|\eta| < 1.0$. Our calculated value along with the statistical and systematic uncertainty is quoted in the section. ?? which matches well within the uncertainties. Eq. 3.5 can be modified to:

$$\frac{\langle dN_{ch}/d\eta \rangle_i}{\langle dN_{ch}/d\eta \rangle} = \frac{\alpha_i \langle N_{trk}^{corr} \rangle_i}{\langle dN_{ch}/d\eta \rangle_{INEL > 0}} \quad (3.6)$$

N_{Trk}^{corr} to N_{ch} correlation factor (α)	
Mult. Class	α - factor
Integrated	1.24 ± 0.000
1.0 - 8.0	1.32 ± 0.000
9.0 - 14.0	1.25 ± 0.000
15.0 - 20.0	1.24 ± 0.000
21.0 - 25.0	1.23 ± 0.000
26.0 - 33.0	1.22 ± 0.000
34.0 - 41.0	1.21 ± 0.000
42.0 - 50.0	1.20 ± 0.000
51.0 - 60.0	1.18 ± 0.000
61.0 - 80.0	1.17 ± 0.001
81.0 - 115.0	1.16 ± 0.003

Table 3.4. The α factors corresponding to each multiplicity bin.

Ratio of evaluated $\langle N_{ch} \rangle$ with MC-truth value (α):

To test the reliability of our result, we have evaluated the $\langle N_{ch} \rangle$ by projecting the N_{Trk}^{corr} - N_{ch} correlation (Fig.3.29) in N_{Trk}^{corr} bins. Then we have taken the ratio of evaluated $\langle N_{ch} \rangle (\alpha_i \times N_{Trk}^{corr}(Bin))$ with the projected value of $\langle N_{ch} \rangle$ from MC truth. This is shown in the Fig.3.31.

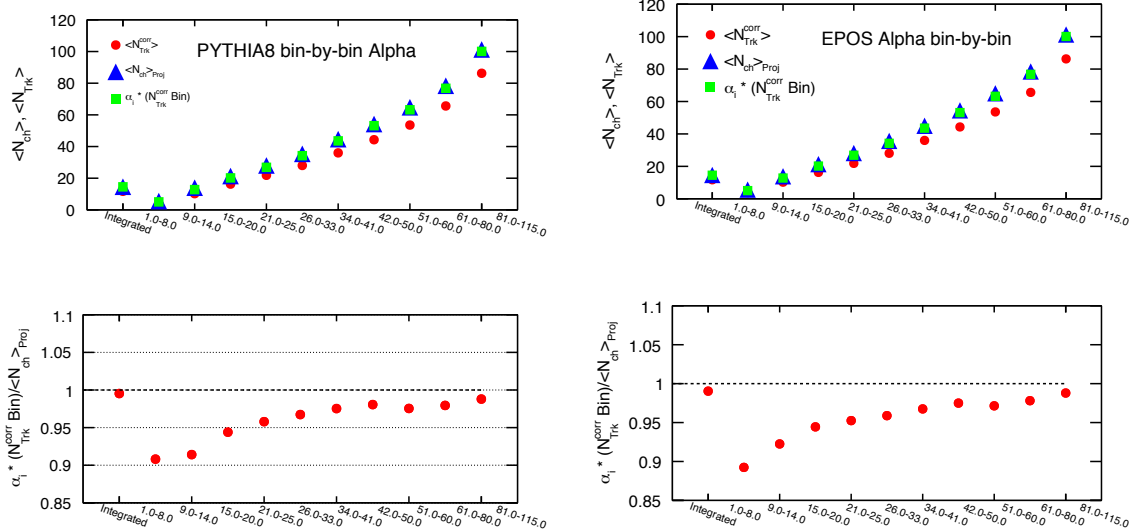


Figure 3.31. $\langle N_{Trk}^{corr} \rangle$, evaluated $\langle N_{ch} \rangle$ and projected $\langle N_{ch} \rangle$ value for PYTHIA8 and EPOS, using bin-by-bin alpha. The lower panels are the ratio of evaluated value of $\langle N_{ch} \rangle$ to projected value of $\langle N_{ch} \rangle$ [116].

From Fig.3.31, it can be seen that the evaluated $\langle N_{ch} \rangle$ is not reproducing well the MC-truth value. We found a maximum deviation of around 10 % for first few multiplicity bins. The large deviation between the MC-truth $\langle N_{ch} \rangle$ value and the evaluated $\langle N_{ch} \rangle$ value reveals that the correlation between N_{Trk}^{corr} and N_{ch} is not perfectly linear and not even in the multiplicity intervals, we are considering. The deviation is large in first few multiplicity bins and becoming smaller towards the higher multiplicity bins. The disagreement between the evaluated $\langle N_{ch} \rangle$ value and $\langle N_{ch} \rangle$ from MC-truth disappears, when the correlation between the N_{Trk}^{corr} and N_{ch} is studied with an add-hoc polynomial which is completely taking care of the shape of N_{Trk}^{corr} versus N_{ch} . The detailed about

the methodology to evaluate $\langle N_{ch} \rangle$ using add-hoc polynomial is discussed in the section.3.3.1. Similar test has been performed taking global α and this is shown in the Fig.3.32, where we have found a very large deviation from the $\langle N_{ch} \rangle$ of MC-truth.

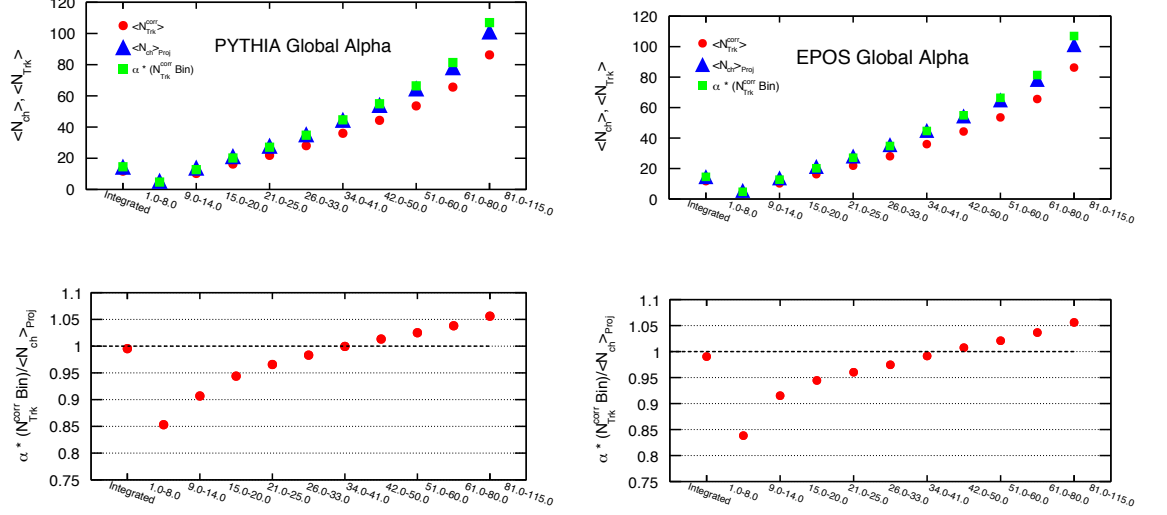


Figure 3.32. $\langle N_{Trk}^{corr} \rangle$, evaluated $\langle N_{ch} \rangle$ and projected $\langle N_{ch} \rangle$ value for PYTHIA8 and EPOS using global α . The lower panels are the ratio of evaluated value of $\langle N_{ch} \rangle$ to projected value of $\langle N_{ch} \rangle$ [116].

Method2

As the N_{ch} to N_{trk}^{corr} correlation is not perfectly linear, it has been proposed to use an add-hoc polynomial function for fitting the correlation [121], which will take care of the complete pattern of the “ N_{ch} vs. N_{trk}^{corr} ” behavior. This is shown in the Fig. 3.33. The add-hoc polynomial is given by,

$$f(x) = \begin{cases} ax^c + b & \text{for } x < x_0, \\ a2x^c + b2 & \text{for } x \geq x_0, \end{cases} \quad (3.7)$$

where,

$$a2 = \left(\frac{ac}{c_2}\right) x_0^{c-c_2} \quad \text{and} \quad b2 = \left(\frac{a-ac}{c_2}\right) x_0^c + b$$

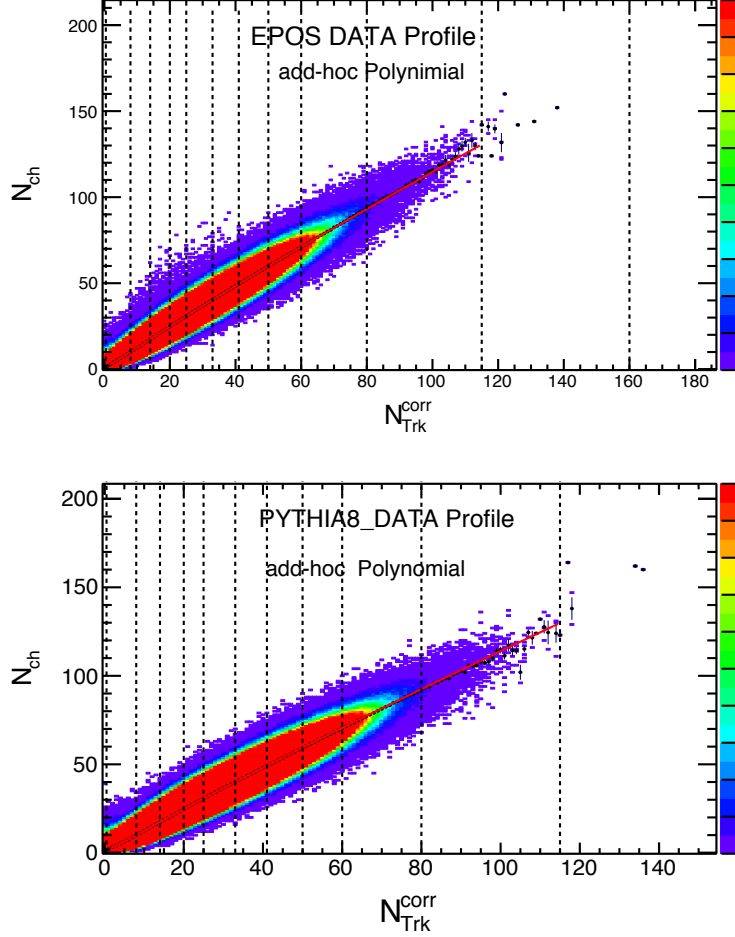


Figure 3.33. N_{tr}^{corr} to N_{ch} correlation plot using data profile for the correction for PYHTIA8 and EPOS, where vertical lines represents the multiplicity bins chosen for the analysis. The fit (red line) is the global fitting to the integrated multiplicity using add-hoc polynomial [116].

We have performed the fitting of N_{ch} vs. N_{trk}^{corr} correlation with Eq. 3.7 to the whole range (0 to ∞). Thereafter, using the same parametrized function (let it be f), we have evaluated $\langle N_{ch} \rangle$ in respective multiplicity bins as shown in the figure.

The $\langle N_{ch} \rangle$ in each multiplicity bin is calculated as,

$$\langle N_{ch} \rangle = \frac{\sum_{i=1}^{n_{bins}} n_i x_i}{\sum_{i=1}^{n_{bins}} n_i} \quad (3.8)$$

where, x_i and n_i are number of events and N_{ch} evaluated in N_{Trk}^{corr} bins ($x_i = f \rightarrow Eval(N_{Trk}^{corr})$). n_{bin} is the number of bins in N_{Trk}^{corr} intervals. It it to be noted here that, n_i value is taken from data. In other words, MC is weighted like data. The $\langle N_{ch} \rangle$ value evaluated in the multiplicity bins is tabulated in the table.3.5. The systematic uncertainty related to evaluation of $\langle N_{ch} \rangle$ will be discussed in the following section.

$\langle N_{ch} \rangle$ using add-hoc polynomial	
Multiplicity Class	$< N_{ch} >$
Integrated	14.66 ± 0.005
1.0 - 8.0	5.63 ± 0.004
9.0 - 14.0	14.03 ± 0.002
15.0 - 20.0	21.43 ± 0.002
21.0 - 25.0	28.12 ± 0.003
26.0 - 33.0	35.45 ± 0.004
34.0 - 41.0	44.70 ± 0.006
42.0 - 50.0	54.22 ± 0.010
51.0 - 60.0	64.71 ± 0.016
61.0 - 80.0	78.16 ± 0.045
81.0 - 115.0	100.74 ± 0.206

Table 3.5. The evaluated $\langle N_{ch} \rangle$ values using add-hoc polynomial

Ratio of evaluated $\langle N_{ch} \rangle$ with MC-truth value (add-hoc polynomial):

Similarly as previous method, to test the reliability of the evaluated $\langle N_{ch} \rangle$, we have compared it with the $\langle N_{ch} \rangle$ MC-truth value. This is shown in Fig. 3.34.

It can be seen from the figure that, this method well reproduces the $\langle N_{ch} \rangle$ MC-truth value. A maximum of only 1% deviation has been found. The method describes the $\langle N_{ch} \rangle$ MC-truth value much better as compared to Method1: 3.3.1. This is due to the fact that the correlation between N_{Trk}^{corr} and N_{ch} is properly taken care of add-hoc polynomial. The $\langle N_{ch} \rangle$ value calculated using this method will be used as the centralized value for the final calculation.

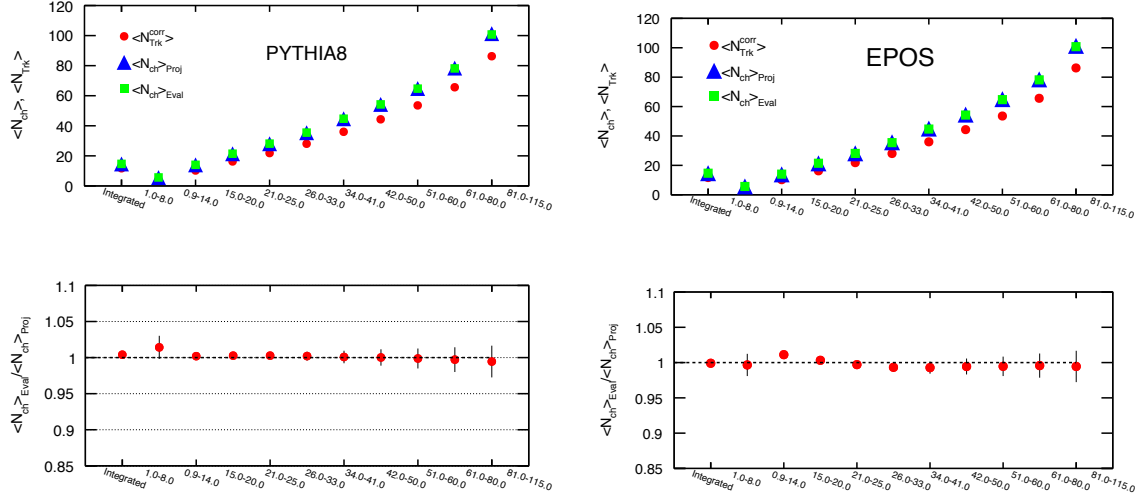


Figure 3.34. Evaluated $\langle N_{ch} \rangle$ and projected $\langle N_{ch} \rangle$ value (MC-truth value) for PYTHIA8 and EPOS, using add-hoc polynomial. The lower panels are the ratio of evaluated values of $\langle N_{ch} \rangle$ to projected values of $\langle N_{ch} \rangle$ [116].

Comparison of Method1 and Method2

To check the consistency between Method1. 3.3.1 and Method2. 3.3.1, we have evaluated the ratio of the value of $\langle N_{ch} \rangle$ obtained from the two methods (α and add-hoc polynomial). The result is shown in the Fig.3.35. It can be seen from the figure that, the two methods are not consistent with each other. We found a maximum of 11% difference between the two methods. For the current analysis, we are using the $\langle N_{ch} \rangle$ value obtained using Method2. 3.3.1 as it is well reproducing the MC-truth $\langle N_{ch} \rangle$ value. The difference between the two discussed method is assigned as systematic uncertainty and is taking care of the systematic uncertainty from non-linearity within it. The systematic

uncertainty associated with α and $\langle N_{ch} \rangle$ from add-hoc polynomial method is discussed in the systematic section (section. 3.3.6).

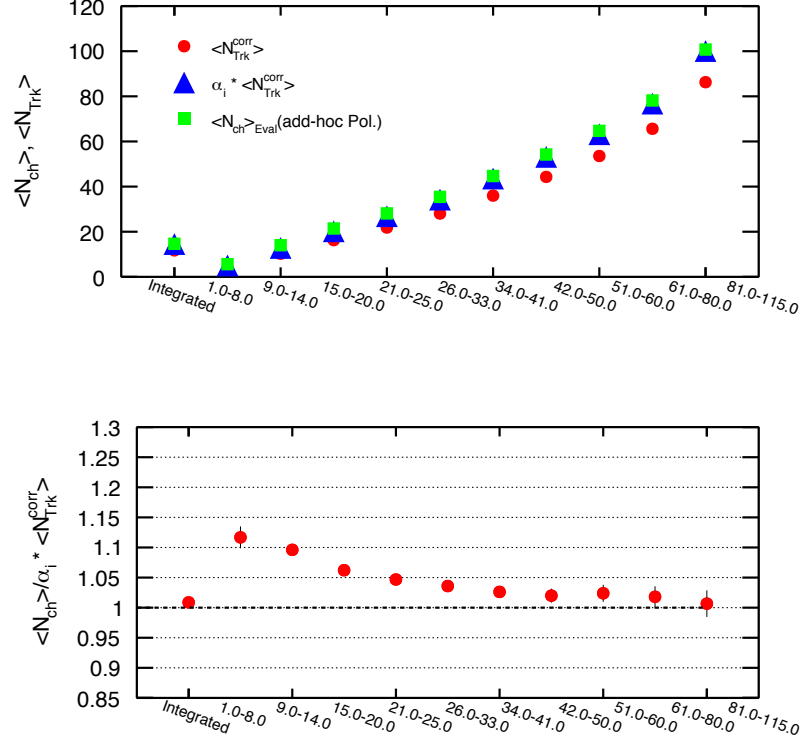


Figure 3.35. $\langle N_{Trk}^{corr} \rangle$, evaluated $\langle N_{ch} \rangle$ using add-hoc polynomial and evaluated $\langle N_{ch} \rangle$ using α . The lower panel is the ratio of evaluated value of $\langle N_{ch} \rangle$ using add-hoc polynomial to the $\langle N_{ch} \rangle$ using α from multiplicity bins [116].

Evaluation of $\langle N_{ch} \rangle$ using add-hoc polynomial (Method2), taking minimum as reference

Following all the steps as that of maximum as reference, we have evaluated $\langle N_{ch} \rangle$ using add-hoc polynomial for minimum as reference as well. For this, we have not used α -factor method (Method1) to calculate $\langle N_{ch} \rangle$ any more, as the $\langle N_{ch} \rangle$ value obtained using add-hoc polynomial (Method2) will be used as centralized value because MC-truth $\langle N_{ch} \rangle$ is well reproduced by it. The top panel of Fig. 3.36 shows the mean tracklet correction, whereas the corrected and raw tracklets distribution along with generated charged-particle distribution are

shown in the bottom panel.

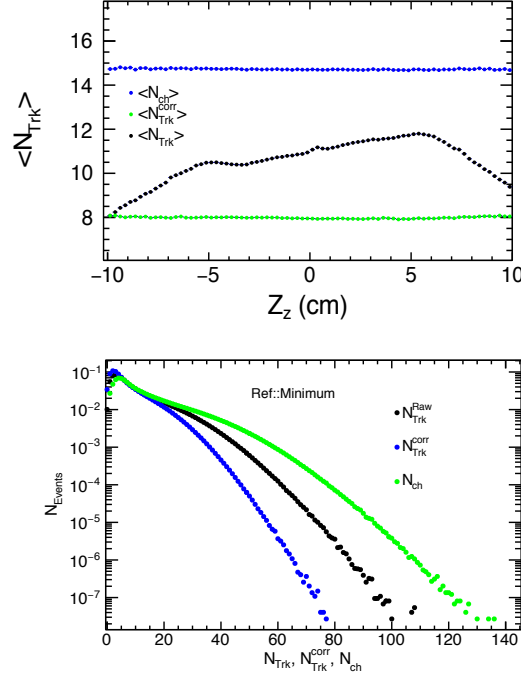


Figure 3.36. (Minimum as reference) Top: Example plot for $\langle N_{Trk} \rangle$ correction taking minimum as reference using PYTHIA8 with data profile. **Bottom:** Example plot of raw tracklet, corrected tracklet (taking minimum as reference) and charged-particle distribution using PYTHIA8 with data profile [116].

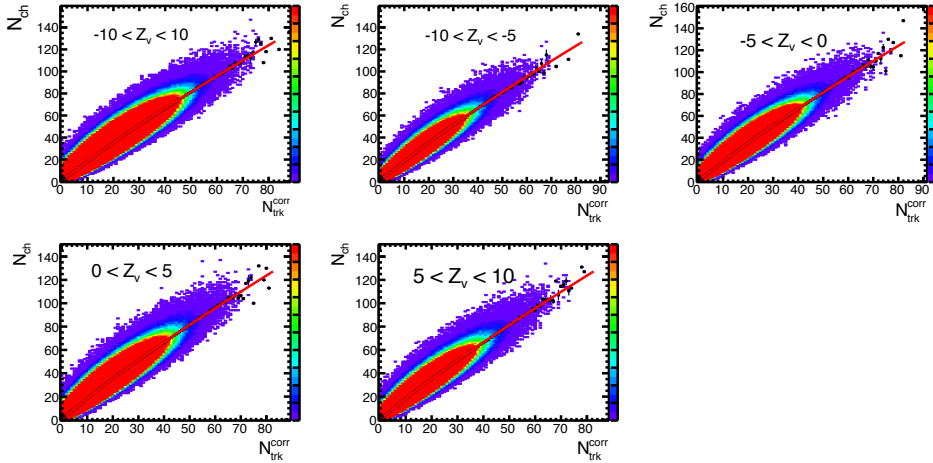


Figure 3.37. (Minimum as reference) N_{tr}^{corr} to N_{ch} correlation in five different Z_v intervals, where tracklets are corrected taking minimum as reference. These are the example plots for PYTHIA8 using data profile for the correction [116].

Minimum as reference	
$\langle N_{ch} \rangle$ using add-hoc polynomial	
Multiplicity Class	$< N_{ch} >$
Integrated	14.670 ± 0.005
1.0 - 5.0	5.820 ± 0.001
6.0 - 10.0	14.200 ± 0.002
11.0 - 14.0	22.350 ± 0.003
15.0 - 17.0	28.450 ± 0.003
18.0 - 23.0	35.470 ± 0.004
24.0 - 28.0	44.590 ± 0.006
29.0 - 34.0	53.120 ± 0.009
35.0 - 42.0	63.450 ± 0.017
43.0 - 54.0	77.000 ± 0.043
55.0 - 83.0	96.37 ± 0.19

Table 3.6. $\langle N_{ch} \rangle$ evaluated using add-hoc polynomial

After, the correction, as usual, we have performed the N_{Trk}^{corr} Vs. N_{ch} correlation study in different Z_v intervals as shown in the Fig. 3.37. Thereafter, we have evaluated the $\langle N_{ch} \rangle$ in multiplicity bins using add-hoc polynomial. The values are tabulated in table.3.6. Here, we need to be careful about the choice of multiplicity binning for minimum as reference. We choose the multiplicity binning in such a way that the $\langle N_{ch} \rangle$ values should be equivalent for both maximum and minimum as reference, so that we can evaluate relative J/ψ at the same $\langle N_{ch} \rangle$ value (x-axis) for both the cases. This will allow us to do a direct comparison for the relative J/ψ between maximum and minimum. The multiplicity binning for minimum can be obtained from the binning of maximum with a shifting factor (f), calculated as,

$$f = \frac{\langle N^{raw} \rangle_{min}}{\langle N^{raw} \rangle_{max}}. \quad (3.9)$$

where $\langle N^{raw} \rangle_{min}$ and $\langle N^{raw} \rangle_{max}$ are minimum and maximum point of raw $\langle N_{Trk} \rangle$ vs. $Z_{ vtx}$. Using this shifting factor (f) the multiplicity bin for minimum is calculated as,

$$N_{Trk}^{min,i} = f \times N_{Trk}^{max,i} \quad (3.10)$$

Here “i” refers to the multiplicity bin edges. In addition to this procedure, we have performed a little adjustment by looking in to the $\langle N_{ch} \rangle$ MC-truth value.

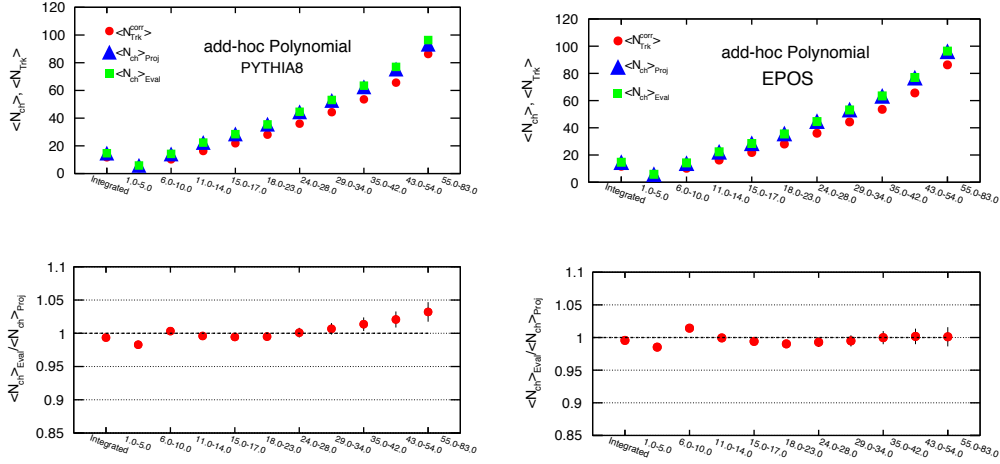


Figure 3.38. (Minimum as reference) Evaluated $\langle N_{ch} \rangle$ and projected $\langle N_{ch} \rangle$ value(MC-truth value) for PYTHIA8 and EPOS, using add-hoc polynomial. The lower panels are the ratio of evaluated value of $\langle N_{ch} \rangle$ to projected value of $\langle N_{ch} \rangle$ [116].

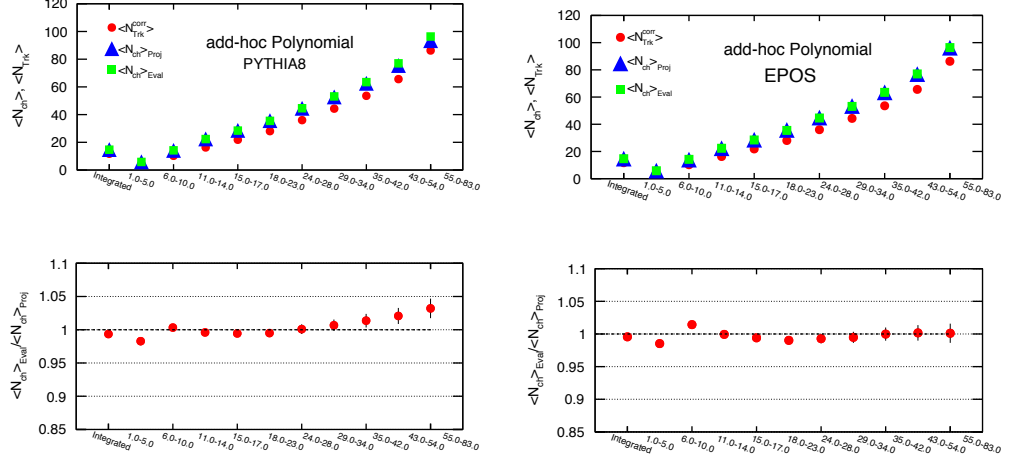


Figure 3.39. (Minimum as reference) Evaluated $\langle N_{ch} \rangle$ and projected $\langle N_{ch} \rangle$ value(MC-truth value) for PYTHIA8 and EPOS, using add-hoc polynomial. The lower panels are the ratio of evaluated value of $\langle N_{ch} \rangle$ to projected value of $\langle N_{ch} \rangle$ [116].

To know the accuracy of the obtained $\langle N_{ch} \rangle$ values, we have studied the ratio of evaluated $\langle N_{ch} \rangle$ to the $\langle N_{ch} \rangle$ from MC-truth and is shown in the Fig.3.39. It can be seen that there is around 2-4% deviation for highest two multiplicity bins for PYTHIA8 MC. But, the EPOS-LHC MC well reproduces the $\langle N_{ch} \rangle$ MC-truth values. The little deviation will be taken care of the systematic uncertainty, as we have taken different MC generators (PYTHIA8 and EPOS) as one of the sources of systematic uncertainty.

3.3.2 Minimum-bias trigger efficiency for $INEL > 0$

The $INEL > 0$ efficiency is defined as the ratio of charged particle distribution “with kINT7” to that of “with out kINT7”. Here, physics selection is applied without any event cuts in both the cases. And, events with at least one physical primary charged-particle is taken ($N_{ch} > 0$), which is the definition of so called $INEL > 0$ events.

$$\epsilon_{INEL>0}^i = \frac{N_{ch}^i \text{ distribution with } kINT7(PS + No \text{ Event cuts})}{N_{ch}^i \text{ distribution without } kINT7(PS + No \text{ Event cuts})} \quad (3.11)$$

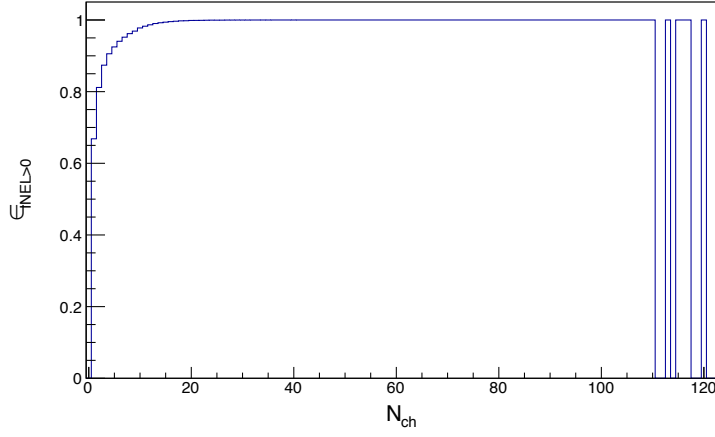


Figure 3.40. Evolution of $INEL > 0$ efficiency with charged-particle [116].

Reference as Maximum			
N_{events} with and w/o kINT7 and $INEL > 0$ efficiency in multiplicity bins			
Mult. class	With kINT7	w/o kINT7	$\epsilon_{INEL>0}$
Integrated	48763130	51602160	0.9445 ± 0.0002
1.0 - 8.0	23862730	26260230	0.9087 ± 0.0003
9.0 - 14.0	8886331	8981902	0.9893 ± 0.0005
15.0 - 20.0	5374087	5381949	0.99854 ± 0.00069
21.0 - 25.0	3023650	3024234	0.99981 ± 0.00081
26.0 - 33.0	3018663	3018941	0.99991 ± 0.00081
34.0 - 41.0	1499562	1500258	0.99954 ± 0.00115
42.0 - 50.0	680444	680763	0.99953 ± 0.00171
51.0 - 60.0	224596	225410	0.99639 ± 0.00297
61.0 - 80.0	61033	61305	0.99556 ± 0.00569
81.0 - 115.0	1914	1926	0.99377 ± 0.03207

Table 3.7. $\epsilon_{INEL>0}$ efficiency in multiplicity bins.

Reference as Minimum			
N_{events} with and w/o and $INEL > 0$ efficiency in multiplicity bins			
Mult. class	With kINT7	w/o kINT7	$\epsilon_{INEL>0}$
Integrated	45889770	48561740	0.94498 ± 0.00019
1.0 - 5.0	20468840	22432550	0.91246 ± 0.00028
6.0 - 10.0	10065050	10191420	0.9876 ± 0.0004
11.0 -14.0	4609855	4610570	0.99984 ± 0.00066
15.0 - 17.0	2380671	2384766	0.99828 ± 0.00091
18.0 - 23.0	2935720	2937508	0.99939 ± 0.00082
24.0 - 28.0	1202879	1203169	0.99976 ± 0.00128
29.0 - 34.0	623963	624144	0.99971 ± 0.00179
35.0 - 42.0	240811	241502	0.99714 ± 0.00287
43.0 - 54.0	49671	49787	0.99767 ± 0.00633
55.0 - 83.0	2748	2785	0.98671 ± 0.02653

Table 3.8. Number of MB events with and w/o and $INEL > 0$ efficiency in multiplicity bins.

The evaluation of $INEL > 0$ efficiency with charged-particle can be seen from Fig.3.40. It can be seen that, for the very first multiplicity bin the efficiency is less than 1 and beyond, the value is almost 1. This can also be observed from tables.3.3.2 and 3.10, where we have calculated the $INEL > 0$ efficiency in each multiplicity bins for reference as maximum and minimum for tracklet correction.

3.3.3 Correction to the first multiplicity bin

As discussed in the section, for the integrated case, we need to correct the yield for all event cuts (trigger and $z_{vtx,QA}^{MB}$) because we want a fully corrected ref-

erence, i.e. the J/ψ -yield and $\langle N_{ch} \rangle$ for all $INEL > 0$ events. In our current analysis we have used the $\langle N_{ch} \rangle$ provided by the multiplicity group. It is indeed fully corrected. Then the order in which you apply the corrections that matters. We first correct for the $z_{vtx,QA}^{MB}$, then for the trigger efficiency, so the trigger efficiency correction should be computed without $z_{vtx,QA}^{MB}$ or any other cuts. This is to correctly account for the correlations between the cuts, e.g. for the fact that the trigger efficiency is different for events passing or not passing the $z_{vtx,QA}^{MB}$. But for the first multiplicity bin, the situation is bit different. We need to correct the yield and $\langle N_{ch} \rangle$ of the selected data sample. If the cuts select events with slightly higher multiplicity in average, but the yield is correctly measured for those selected events, then the correlation is preserved and we suppose that the result (yield vs $\langle N_{ch} \rangle$) is fine. Based on that we can decide which correction is worth to be applied.

We suppose that $z_{vtx,QA}^{MB}$ affects the events same way events with or without a J/ψ in it, so it does not bias the yield calculation. Of course it rejects more events at low multiplicity so the $\langle N_{ch} \rangle$ of the events with this cut is higher than without the cut. But, we suppose that the yield correctly corresponds to the events that we have selected so it will also change consistently and the correlation is preserved. Therefore, we suppose we do not need to correct for $z_{vtx,QA}^{MB}$. The trigger selection, on the other hand, likely affects differently events with or without a J/ψ (as the J/ψ decay muons fire the V0C). Therefore, the yield is biased because of this cut and it has to be corrected. Since, we correct the yield, also the $\langle N_{ch} \rangle$ must be corrected consistently. In the first bin, we only correct for the trigger efficiency, and this correction applies to events selected with all other cuts. So the correction in this case must be computed with all other cuts applied ($N_{Tracklets}$ correction uses $z_{vtx,QA}^{MB}$ and the z_{vtx} cuts).

Correction to the yield of 1st multiplicity bin:

$$\epsilon_{INEL>0,yield}^1 = \frac{N_{events}[N_{ch} \geq 1 + PS(kINT7) + vtxQA + z_{vtx}]}{N_{events}[N_{ch} \geq 1 + vtxQA + z_{vtx}]} \quad (3.12)$$

We have computed the factor using EPOS and PYTHIA8.

N_{events} corresponds to numerator and denominator of Eq. 3.16			
MC	$N_{events} [N_{ch} \geq 1 + PS(kINT7) + vtxQA + z_{vtx}]$	$N_{Events} [N_{ch} \geq 1 + vtxQA + z_{vtx}]$	$\epsilon_{INEL>0,yield}^1$
PYTHIA8	5556537.0	6109334.0	0.9095
EPOS	9930705.0	10762060.0	0.922

Table 3.9.

Therefore, we have computed the Correction factor and this is 0.916 ± 0.006 (0.6 % syst.). This correction factor should be multiply to the yield.

Correction to $\langle N_{ch} \rangle$ of 1^{st} multiplicity bin:

$$\epsilon_{INEL>0,\langle N_{ch} \rangle}^1 = \frac{\langle N_{ch} \rangle [N_{ch} \geq 1 + PS(kINT7) + vtxQA + z_{vtx}]}{\langle N_{ch} \rangle [N_{ch} \geq 1 + vtxQA + z_{vtx}]} \quad (3.13)$$

We have computed the factor using EPOS and PYTHIA8.

$\langle N_{ch} \rangle$ corresponds to numerator and denominator of Eq. 3.13			
MC	$\langle N_{ch} \rangle [N_{ch} \geq 1 + PS(kINT7) + vtxQA + z_{vtx}]$	$\langle N_{ch} \rangle [N_{ch} \geq 1 + vtxQA + z_{vtx}]$	$\epsilon_{INEL>0,\langle N_{ch} \rangle}^1$
PYTHIA8	5.708	5.512	1.035
EPOS	5.683	5.457	1.0414

Table 3.10.

Therefore, we have computed the Correction factor to be 1.038 ± 0.0032 (0.32% Syst.). This correction factor should be divide to relative $\langle N_{ch} \rangle$.

3.3.4 Correction for $INEL = 0$ contamination

As $INEL > 0$ condition is applied using MC, therefore, for data we included some contamination of $INEL = 0$ events. This factor should be evaluated and corrected to the yield.

The combination of vtxQA and $INEL=0$ contamination corrections of MB events can be done in two ways:

- **Correct for vtxQA from data then correct for the contamination w/o vtxQA**

From the section 3.1.2 we have $\epsilon_{vtx,QA}^{MB} = 0.94$.

$$\frac{N_{Events}(N_{ch}=0 \text{ and } w/o \text{ } vtxQA+kINT7)}{N_{Events}(N_{ch}\geq 0 \text{ and } w/o \text{ } vtxQA+kINT7)} = 0.02 \quad (3.14)$$

Correction factor = $(1.0 - 0.02)/0.94 = 1.04$.

- **Correct for the contamination with vtxQA then correct for vtxQA from MC**

$$\epsilon_{vtx,QA}^{MB}(MC, INEL > 0) = \frac{N_{Events}(N_{ch}=0 \text{ and with } VtxQA+INT7)}{N_{Events}(N_{ch}=0 \text{ and } w/o \text{ } VtxQA+INT7)} = 0.962 \quad (3.15)$$

$$\frac{N_{Events}(N_{ch}=0 \text{ and with } vtxQA+kINT7)}{N_{Events}(N_{ch}\geq 0 \text{ and with } vtxQA+kINT7)} = 0.008 \quad (3.16)$$

Correction factor = $(1.0 - 0.008)/0.962 = 1.03$.

The correction factors mentioned above are calculated using PYTHIA8. We have recalculated the correction factor using EPOS and the difference between two MCs (PYTHIA8 and EPOSLHC) on contamination factor is found to be 0.5%. In addition to this, the comparison between the above two methods give 1% difference.

$INEL = 0$ contamination factor is calculated as,
 $\epsilon_{INEL=0} = 1.0/(1.0 - 0.02) = 1.02 \pm 0.015$ (syst. error).

3.3.5 Correction for pileup events

For our current analysis, we have used the second argument of “AddTaskPhysicsSelection(kFALSE,kTRUE,0,kFALSE)” as “kTRUE” to remove the pile up events. The pileup efficiency factor can be calculated by comparing MB events with and without pileup cuts using MC, as MC does not contain pileup. Table 3.11 shows the pileup factors for low pileup and high pileup runs.

$$\epsilon_{pu}^{MB,i} = \frac{N_{INT7}^i / N_{INT7\ w/o\ pileup}^{total}}{N_{INT7}^i / N_{INT7\ with\ pileup}^{total}} \quad (3.17)$$

Pileup factor for high and low pileup runs		
Mult. class	$\epsilon_{pu}^{MB,i} (\mu > 0.006)$	$\epsilon_{pu}^{MB,i} (\mu < 0.006)$
1.0 - 8.0	0.999968 ± 0.000714	0.999696 ± 0.001264
9.0 - 14.0	0.999795 ± 0.001038	0.999914 ± 0.001835
15.0 - 20.0	1.001000 ± 0.001293	1.00034 ± 0.00230
21.0 - 25.0	0.999309 ± 0.001682	1.00117 ± 0.00298
26.0 - 33.0	1.00053 ± 0.00169	0.999991 ± 0.002979
34.0 - 41.0	0.99866 ± 0.00236	0.998542 ± 0.004143
41.0 - 50.0	1.00087 ± 0.00349	1.00125 ± 0.00612
51.0 - 60.0	1.00087 ± 0.00349	1.00921 ± 0.01071
61.0 - 80.0	0.99736 ± 0.00601	1.00061 ± 0.02036
81.0 - 115.0	1.00429 ± 0.01175	0.992776 ± 0.110446

Table 3.11. Pileup factor for high and low pileup runs in the multiplicity bins.

For all the multiplicity bins, we have found the pileup efficiency factor to be very close to 1.

3.3.6 Systematic uncertainty in N_{Trk}^{corr} to N_{ch} correction factor

The possible sources of systematic uncertainty in N_{Trk}^{corr} to N_{ch} correction factor will be:

- The chosen profile for the correction: As the correction is performed using the CINT7 profile integrated over all the periods with proper equalization, so the correlation factor should not differ, if we choose a TProfile from data or MC(kINT7). This is because the data and MC should be alike.
- The chosen Z_v interval: As we have equalized the multiplicity along Z_v , so the N_{Trk}^{corr} to N_{ch} correlation factor should not differ with Z_v . For the current analysis, we have chosen four Z_v interval: (1) $-10.0 < Z_v < -5.0$, (2) $-5.0 < Z_v < 0.0$, (3) $0.0 < Z_v < 5.0$ and $5.0 < Z_v < 10.0$, to account for tit's effect in systematic uncertainty.
- The Chosen MC data sample: To see the effect of MC generators, we have taken two samples of MC data which are PYTHIA8 and EPOSLHC. With the proper equalization we have added 5 periods anchored to LHC16h, 16j, 16k, 16o, 16p for PYTHIA8 and are used for the analysis. For EPOSLHC, the only available MC sample is for LHC 16k period.
- The chosen methods: The systematic difference between Method1. 3.3.1 and Method2. 3.3.1 will be assigned as systematic uncertainty. The systematic uncertainty associated with this is very less (less than 1%), therefore we ignore it.

Taking all the combinations, we have performed around 20 tests for all the multiplicity intervals for both the methods, Method1. 3.3.1 and Method2. 3.3.1. Similar procedure has been opted for both the cases taking maximum as reference and minimum as reference for the multiplicity correction.

Similar to the procedure opted for signal, from the 20 tests, the linear average of the corresponding statistical uncertainties in each test is assigned as

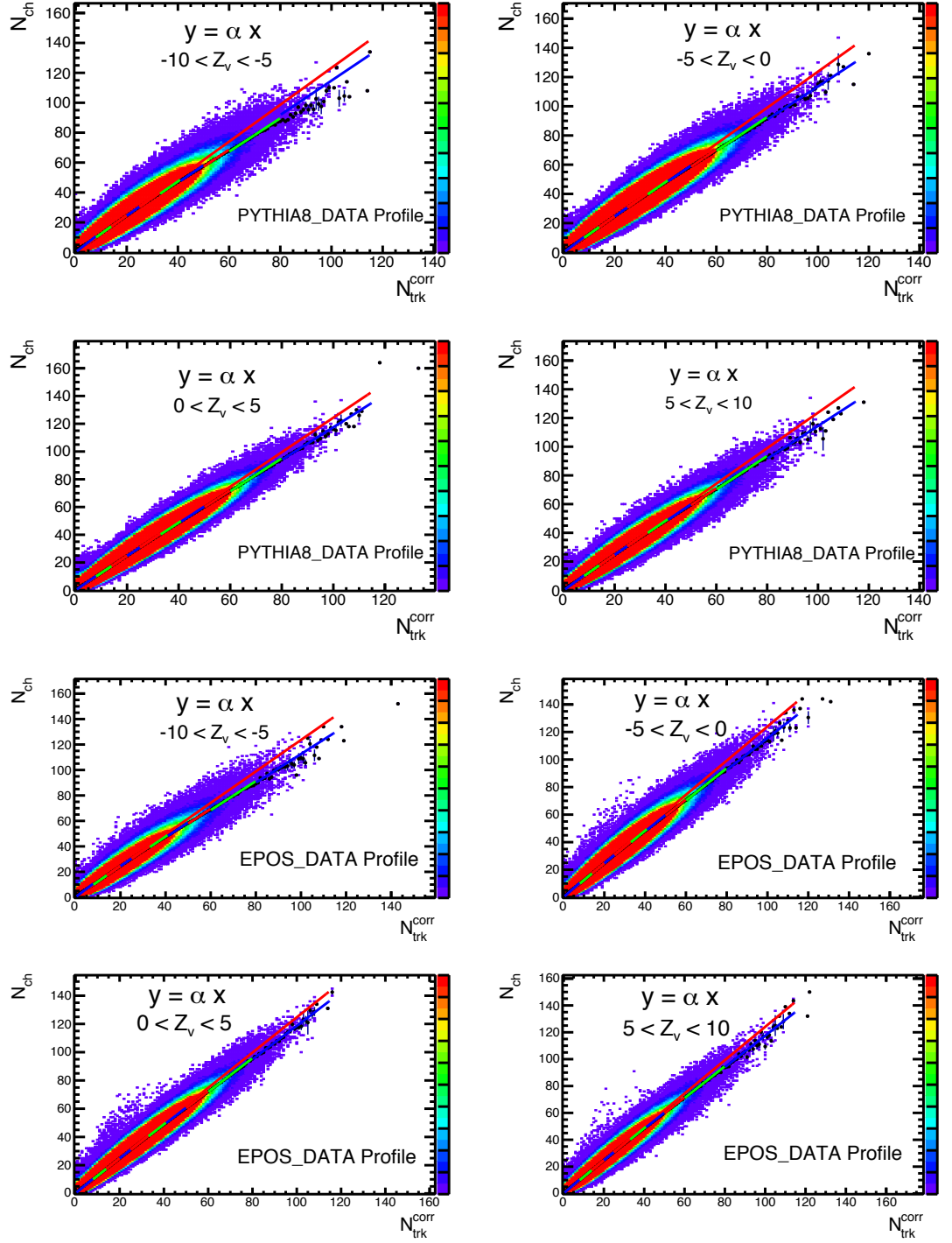


Figure 3.41. (Example plots for maximum as reference) The N_{trk}^{corr} to N_{ch} correlation plot for integrated periods (anchored to LHC 16h + 16j + 16k + 16o + 16p) of PYTHIA8 and EPOS (anchored to LHC 16k) in four Z_v intervals and is fitted with the function $y = \alpha \times x$. The vertical lines represent the multiplicity bins chosen for the analysis. The red lines represent the fits to integrated multiplicity and the small-colored lines represent fit in multiplicity bins [116].

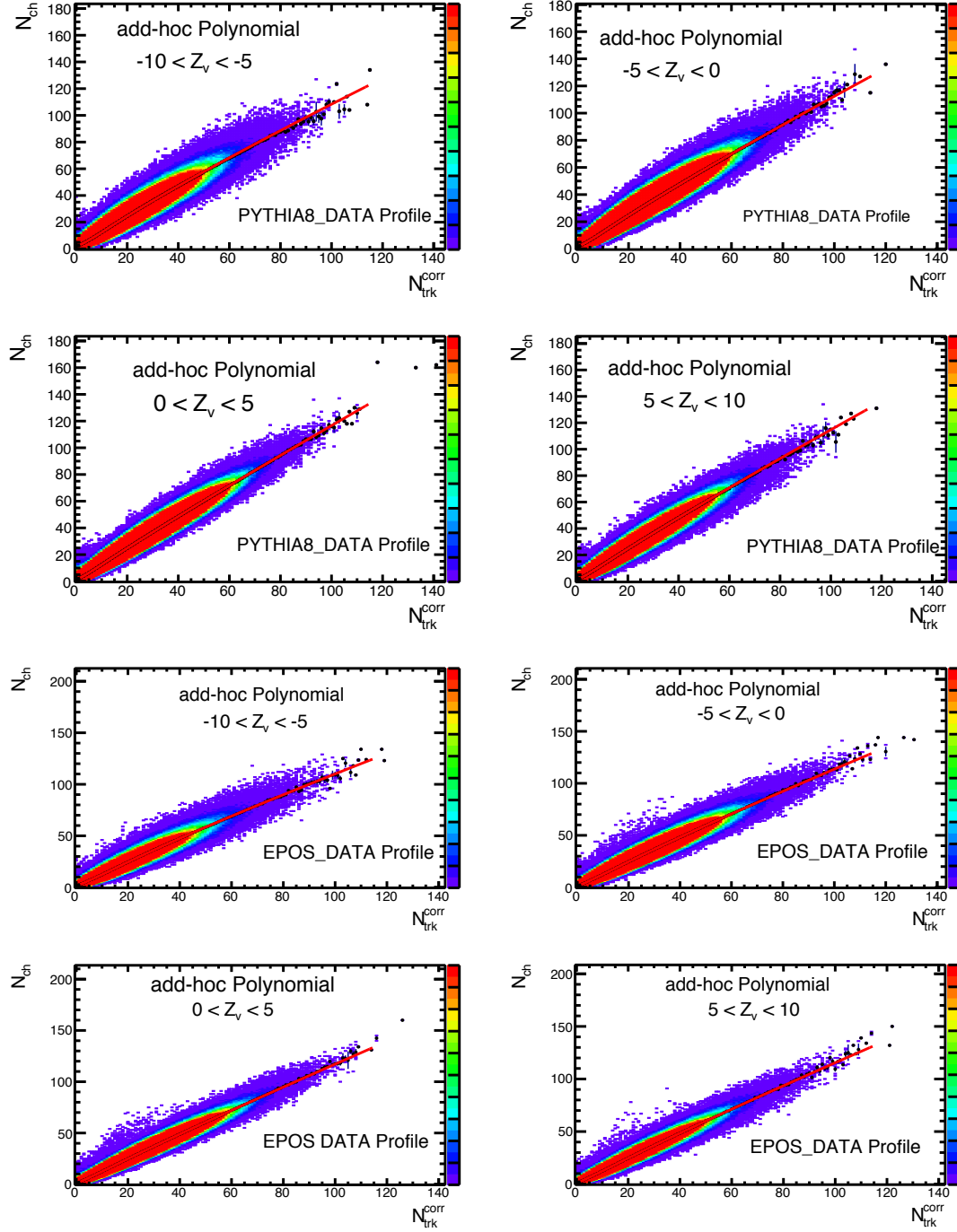


Figure 3.42. (Example plot for maximum as reference) The N_{trk}^{corr} to N_{ch} correlation plot for integrated periods (anchored to LHC 16h + 16j + 16k + 16o + 16p) of PYTHIA8 and EPOS LHC (anchored to LHC 16k) in four Z_v intervals and is fitted with the add-hoc polynomial function(3.7). The vertical lines represents the multiplicity bins chosen for the analysis. The red lines represent the fits to integrated multiplicity and the small color lines represent fit in multiplicity bin [116].

the statistical uncertainty for each bin and the RMS of the distribution of the test is used as the corresponding systematic uncertainty. This is shown in the

Fig. 3.43 and Fig. 3.44 for the multiplicity bin (0.5, 8.0) using Method1. 3.3.1 and Method2. 3.3.1. Here the abbreviation of x-axis for each test, for example "PYTHIA8_DATAProf_Zv_m10_m5" represents "MC + TProfile + Z_v - range". The details about the systematic uncertainty of α - factor and $\langle N_{ch} \rangle$ from add-hoc polynomial, in all the multiplicity bins from all the combinations along with the statistical and systematic uncertainty, can be observed from the figures in the sections 8.9 . For the completeness, we have tabulated the mean value, statistical uncertainty and systematic uncertainty of α - factor and $\langle N_{ch} \rangle$ using add-hoc polynomial in the table. 3.12, table. 3.13 and table. 3.14.

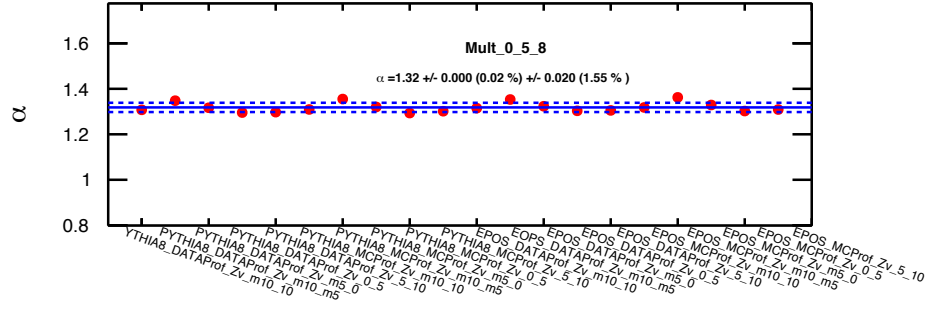


Figure 3.43. Value of α -parameter in different set of tests for the multiplicity bin (1.0, 8.0) [116].

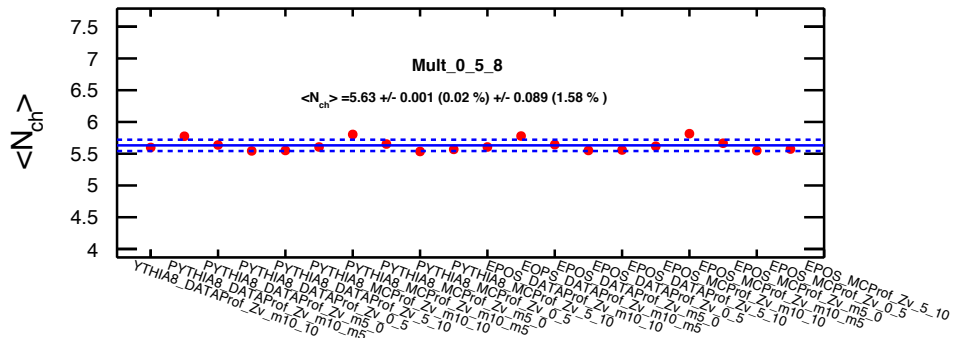


Figure 3.44. Value of $\langle N_{ch} \rangle$ using add-hoc polynomial in different set of tests for the multiplicity bin (1.0, 8.0) [116].

$\alpha - factor$ along with the statistical and systematic error			
Mult. Class	$\alpha - factor$	Stat. Error	Syst. Error
Integrated	1.24	0.000 (0.01 %)	0.004 (0.31 %)
1.0 - 8.0	1.32	0.000 (0.02 %)	0.020 (1.55 %)
9.0 - 14.0	1.25	0.000 (0.02 %)	0.003 (0.23 %)
15.0 - 20.0	1.24	0.000 (0.02 %)	0.004 (0.30 %)
21.0 - 25.0	1.23	0.000 (0.02 %)	0.005 (0.41 %)
26.0 - 33.0	1.22	0.000 (0.02 %)	0.007 (0.59 %)
34.0 - 41.0	1.21	0.000 (0.02 %)	0.010 (0.86 %)
42.0 - 50.0	1.20	0.000 (0.03 %)	0.014 (1.14 %)
51.0 - 60.0	1.18	0.000 (0.04 %)	0.017 (1.43 %)
61.0 - 80.0	1.17	0.001 (0.07 %)	0.021 (1.80 %)
81.0 - 115.0	1.16	0.003 (0.25 %)	0.023 (1.98 %)

Table 3.12. $\alpha - factor$ along with the statistical and systematic error in each multiplicity bins

$\langle N_{ch} \rangle$ value using add-hoc polynomial for maximum as reference			
Mult. class	$\langle N_{ch} \rangle$ -value	Stat. Error	Syst. Error
Integrated	14.66	0.005 (0.03 %)	0.038 (0.26 %)
1.0 - 8.0	5.63	0.001 (0.02 %)	0.089 (1.58 %)
9.0 - 14.0	14.03	0.002 (0.01 %)	0.038 (0.27 %)
15.0 - 20.0	21.43	0.002 (0.01 %)	0.062 (0.29 %)
21.0 - 25.0	28.12	0.003 (0.01 %)	0.113 (0.40 %)
26.0 - 33.0	35.45	0.004 (0.01 %)	0.215 (0.61 %)
34.0 - 41.0	44.70	0.006 (0.01 %)	0.388 (0.87 %)
42.0 - 50.0	54.22	0.010 (0.02 %)	0.615 (1.14 %)
51.0 - 60.0	64.71	0.016 (0.03 %)	0.896 (1.38 %)
61.0 - 80.0	78.16	0.045 (0.06 %)	1.343 (1.72 %)
81.0 - 115.0	100.74	0.206 (0.20 %)	2.211 (2.20 %)

Table 3.13. $\langle N_{ch} \rangle$ value using add-hoc polynomial in the multiplicity bins for maximum as reference.

$\langle N_{ch} \rangle$ value using add-hoc polynomial for minimum as reference			
Mult. class	$\langle N_{ch} \rangle$-value	Stat. Error	Syst. Error
Integrated	14.67	0.005 (0.03 %)	0.076 (0.52 %)
1.0 - 5.0	5.82	0.001 (0.02 %)	0.036 (0.61 %)
6.0 - 10.0	14.20	0.002 (0.02 %)	0.070 (0.49 %)
11.0 -14.0	22.35	0.003 (0.01 %)	0.109 (0.49 %)
15.0 - 17.0	28.45	0.003 (0.01 %)	0.149 (0.53 %)
18.0 - 23.0	35.47	0.004 (0.01 %)	0.213 (0.60 %)
24.0 - 28.0	44.59	0.006 (0.01 %)	0.325 (0.73 %)
29.0 - 34.0	53.12	0.009 (0.02 %)	0.455 (0.86 %)
35.0 - 42.0	63.45	0.017 (0.03 %)	0.639 (1.01 %)
43.0 - 54.0	77.00	0.043 (0.06 %)	0.910 (1.18 %)
55.0 - 83.0	96.37	0.190 (0.20 %)	1.364 (1.42 %)

Table 3.14. $\langle N_{ch} \rangle$ value using add-hoc polynomial in the multiplicity bins for minimum as reference

The following points can be concluded from the systematic uncertainty study:

The sources of systematic uncertainties have similar effects for α -factor method and add-hoc polynomial method. This can be seen from the systematic uncertainties shown in Fig.3.43, Fig.3.44 and from the figures in the appendix section .8.9.

- We found a maximum systematic uncertainty associated with α -factor and $\langle N_{ch} \rangle$ from add-hoc as 1.98% and 2.2%, respectively.
- The systematic from minimum as reference is little less than that of maximum as reference. This is due to the fact that Z_{vtx} equalization is better for minimum as compared to maximum.
- We found a maximum systematic uncertainty of 6.06 % from the non-linearity i.e the systematic difference between bin-by-bin α and global α factor.

Now, in the next chapter, we proceed to discuss the detailed methodology for measurement of J/ψ using muon spectrometer, followed by results and discussions.

Chapter 4

Forward Rapidity J/ψ Measurement

¹We are interested in the study of J/ψ production with event multiplicity in pp collisions. The estimation of the event multiplicity has been discussed in chapter.4. In this chapter, our focus is to discuss the J/ψ yield and $\langle p_T \rangle$ measurement. The goal of the analysis is to study the evolution of relative quantities: $Y^{J/\psi} / \langle Y^{J/\psi} \rangle$ and $\langle p_T^{J/\psi} \rangle / \langle p_T^{J/\psi} \rangle_{MB}$ with relative charged-particle pseudorapidity density. The advantages of the study is that several correction factors cancel out in relative quantities and it's easy to compare the results across collision systems and center-of-mass energies. The J/ψ are measured in the di-muon decay channel with the ALICE muon spectrometer. The usual procedure is followed to measure the J/ψ yield which is extracted from invariant mass spectra in a certain kinematical range. Another important observable is the first moment of transverse momentum distribution, $\langle p_T \rangle$, which carries information about the particle production mechanism. In this chapter, we have performed the measurement of $\langle p_T \rangle$ and its dependence of event averaged charged-particle multiplicity. The $\langle p_T \rangle$ has been extracted using di-muon transverse momentum invariant mass spectrum, $\langle p_T^{\mu^+\mu^-} \rangle(m_{\mu^+\mu^-})$, as is done for the p-Pb analysis [114]. The advantages of this method is that we do not have to rely on the statistics to construct p_T -spectra to extract the $\langle p_T \rangle$. Hence, this technique is suitable for the precise measurement at high multiplicity regimes,

¹“ J/ψ production as function of charged-particle multiplicity in pp collisions at $\sqrt{s} = 13$ TeV at forward rapidity” Dhananjaya Thakur and Raghunath Sahoo, ANA-734; “Quarkonium production as a function of charged particles multiplicity in pp and p-Pb collisions measured by ALICE at the LHC,” D. Thakur [ALICE Collaboration], PoS HardProbes 2018, 164 (2019)

where the statistics is low, with a thinner binning compared to the standard procedure. In this chapter, a correction method to account for the spectrometer *acceptance* $\times$ *efficiency* and a full study of the systematic uncertainties on the measurements of J/ψ yield and $\langle p_T \rangle$ have been developed.

4.1 J/ψ yield measurement

The number of J/ψ produced per minimum-bias (MB) collision can be obtained as,

$$Y_{J/\psi} = \frac{N_{J/\psi}}{\langle A \times \epsilon \rangle \cdot BR \cdot N_{MB}} \quad (4.1)$$

where, $N_{J/\psi}$ is the number of J/ψ and N_{MB} is the number of minimum-bias (MB) events. $\langle A \times \epsilon \rangle$ is the detector acceptance and efficiency correction factor. BR is the branching ratio of the decay channel, $J/\psi \rightarrow \mu^+ + \mu^-$ and is taken to be 5.961 ± 0.033 [114].

Therefore, the number of J/ψ in i^{th} multiplicity bin and in integrated over multiplicity can be obtained respectively as,

$$Y_{J/\psi}^{bin} = \frac{N_{J/\psi}^{bin}}{\langle A \times \epsilon \rangle \cdot BR \cdot N_{MB}^{bin}} \quad (4.2)$$

$$Y_{J/\psi}^{integrated} = \frac{N_{J/\psi}^{integrated}}{\langle A \times \epsilon \rangle \cdot BR \cdot N_{MB}^{integrated}} \cdot \quad (4.3)$$

A direct comparison of the yield per event in each bin with the inclusive yield per event can be expressed using relative yield as (dividing Eq.4.2 by Eq.4.3):

$$Y_{J/\psi}^{R,bin} = \frac{Y_{J/\psi}^{bin}}{Y_{J/\psi}^{integrated}} = \frac{N_{J/\psi}^{bin}}{N_{J/\psi}^{integrated}} \times \frac{N_{MB}^{total}}{N_{MB}^{bin}} \times \frac{1}{\epsilon_{MB}}, \quad (4.4)$$

where ϵ_{MB} is the minimum-bias trigger efficiency which includes all the correc-

tion factors. The $\langle A \times \epsilon \rangle$ factor and BR cancel when we calculate the relative yield. This is a major advantage of dealing with ratios. For the J/ψ analysis through di-muon channel, we use di-muon (CMUL7) trigger. Therefore, to calculate the relative J/ψ , we need to find out equivalent number of minimum bias events to be used for the calculation. For this, it is necessary to calculate the di-muon trigger event normalization factor F_{norm} . The equivalent number of MB events (N_{MB}^{eq}) corresponding to the analyzed CMUL sample (N_{CMUL}) is:

$$N_{MB} = F_{Norm} \times N_{CMUL}. \quad (4.5)$$

4.2 Normalization factor calculation

The CMUL trigger used in the analysis has implicit CINT7 (MB) trigger condition. However, the MB trigger was downscaled during the data taking to allow more DAQ bandwidth for the rare trigger like CMUL. To calculate the relative J/ψ , we need to find out equivalent number of minimum bias events. This is given as:

$$N_{MB} = F_{Norm} \times N_{CMUL} \quad (4.6)$$

Therefore the formula for relative yield of J/ψ (Eq.4.4) can be written as:

$$Y_{rel}^i = \frac{N_{J/\psi}^i}{N_{J/\psi}} \times \frac{N_{MB}^{equiv}}{N_{MB}^{equiv,i}} \times \frac{1}{\epsilon_{INEL>0}^{MB}} \quad (4.7)$$

Where N_{MB}^{equiv} and $N_{MB}^{equiv,i}$ are the number of MB events in integrated multiplicity bin and in i^{th} multiplicity bin respectively. The equivalent number of minimum bias events which is mentioned in the Eq. 4.7 can be expressed with number of CMUL events as;

$$N_{MB}^{equiv} = \sum_j F_{Norm}^j N_{CMUL}^j \quad (4.8)$$

$$N_{MB}^{equiv,i} = \sum_j F_{Norm}^{i,j} N_{CMUL}^{i,j} \quad (4.9)$$

The run-by-run sum is performed following Ref. [122]. Here, F_{Norm}^j and $N_{CMUL}^{i,j}$ are the F_{Norm} in integrated and multiplicity bin, which is calculated on run-by-run basis using offline method. Now, the Eq. 4.7 can be rewritten as;

$$Y_{rel}^i = \frac{N_{J/\psi}^i}{N_{J/\psi}} \times \frac{N_{CMUL}}{N_{CMUL}^i} \times \frac{F_{Norm}}{F_{Norm}^i} \times \frac{1}{\epsilon_{INEL>0}^{MB}} \quad (4.10)$$

Where,

$$F_{Norm} = \frac{1}{N_{CMUL}} \times \sum_j F_{Norm}^j N_{CMUL}^j \quad (4.11)$$

$$F_{Norm}^i = \frac{1}{N_{CMUL}^i} \times \sum_j F_{Norm}^{i,j} N_{CMUL}^{i,j} \quad (4.12)$$

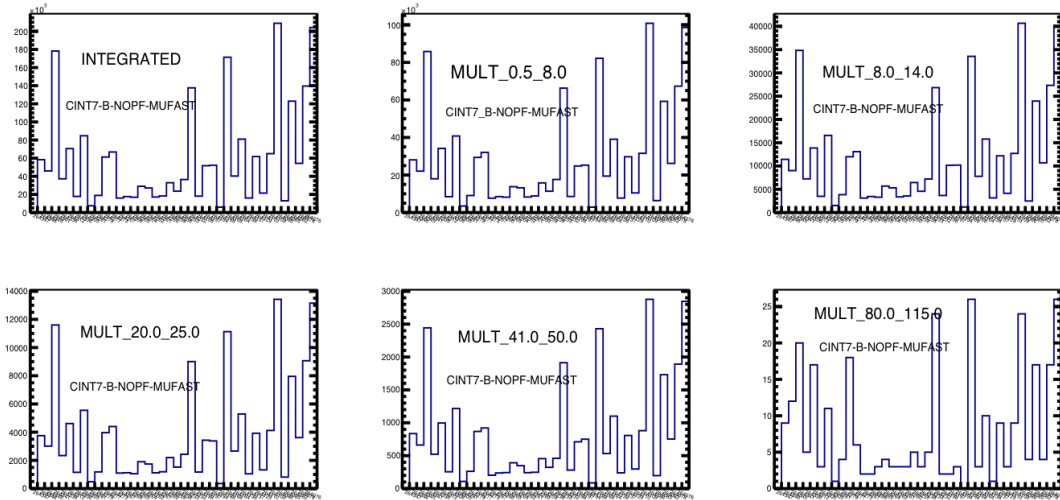


Figure 4.1. Variation of CINT7 (MB) events in run-by-run basis in different multiplicity bins using LHC 16p data [116].

For the current analysis, we have used **Offline2** method to calculate F_{Norm} factor, as the statistics of the MB trigger is low. In this case, an intermediate trigger with higher trigger rate (for example single muon trigger) is used for the calculation.

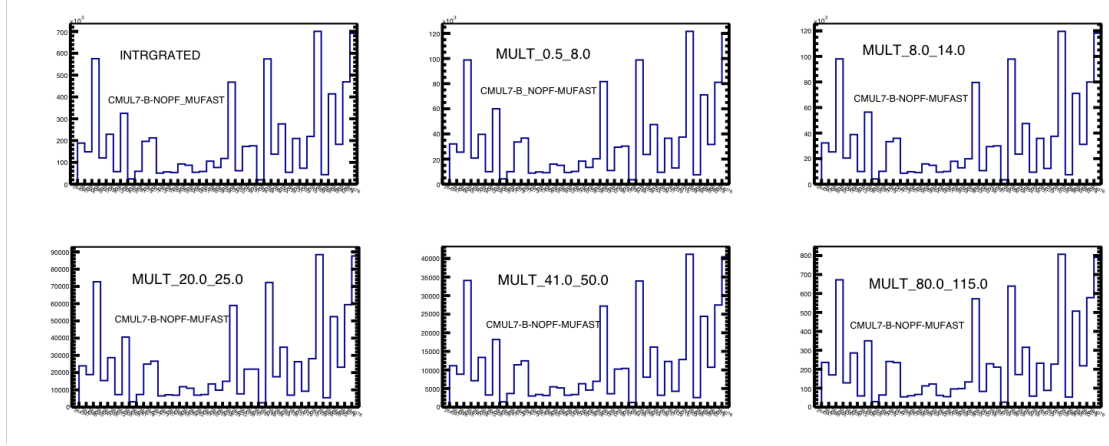


Figure 4.2. Variation of CMUL7 (MB) events in run-by-run basis in different multiplicity bins using LHC 16p data [116].

$$F_{Norm}^{Off2,j} = \frac{MB^j}{MB \& 0MSL^j} \times \frac{MSL^j}{MSL \& 0MUL^j} \quad (4.13)$$

Where,

- MSL is the number of physics selected CMSL7 events
- $MB \& 0MSL$ is the sub sample of MB events containing also the 0MSL trigger input
- $MSL \& 0MUL$ is the sub sample of CMSL7 events containing also the 0MUL trigger input

Eq. 4.13 represents F_{Norm} factor on run-by-run basis. The weighted average of F_{Norm} factor is given by:

$$F_{Norm}^{Offline} = \frac{\sum_j^{runs} F_{Norm}^j N_{CMUL}^j}{\sum_j^{runs} N_{CMUL}^j} \quad (4.14)$$

Using Eq.4.13, the run-by-run F_{Norm} factor in each multiplicity bin is determined as:

$$F_{Norm}^{i,j} = F_{Norm}^j \times \frac{F_{MB}^{i,j}/N_{MB}^j}{N_{CMUL}^{i,j}/N_{CMUL}^j} \quad (4.15)$$

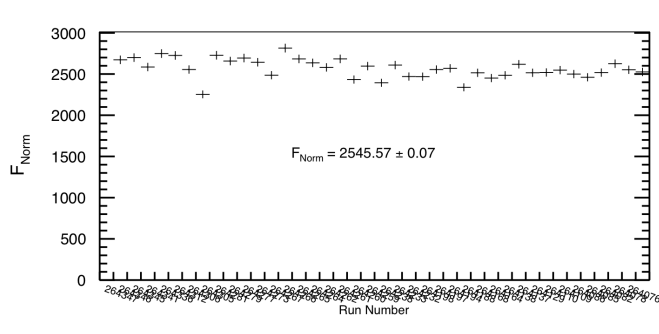


Figure 4.3. Integrated normalization factor in run-by-run basis calculated using Offline2 methods using LHC 16p data [116].

By using Eq. 4.15 in Eq. 4.16, one can obtain the factor, F_{Norm} in each multiplicity bins on run-by-run basis as:

$$F_{Norm}^i = \frac{1}{N_{CMUL}^i} \times \sum_j F_{Norm}^j N_{CMUL}^j N_{MB}^{i,j} / N_{MB}^j \quad (4.16)$$

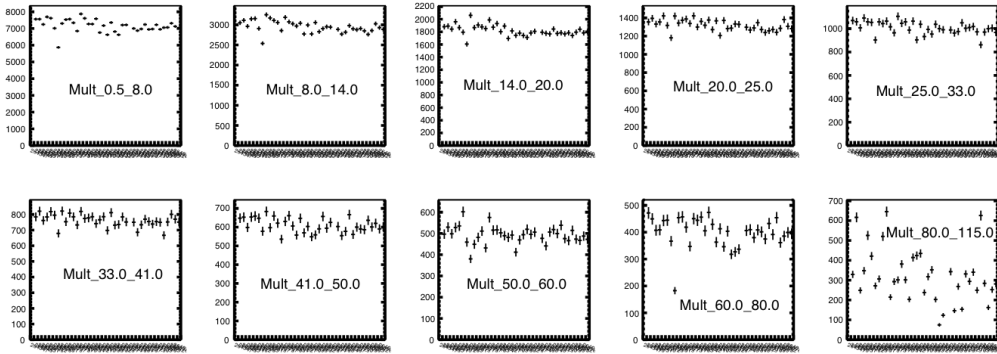


Figure 4.4. Normalization factor in run-by-run basis for different multiplicity bins calculated using Offline2 methods using LHC 16p data [116].

Therefor the formula for relative yield calculation (Eq.4.10) can be modified as;

$$\frac{\frac{dN_{J/\psi}}{dy}}{\langle \frac{dN_{J/\psi}}{dy} \rangle} = \frac{N_{J/\psi}^i}{N_{J/\psi}^{tot}} \times \frac{\sum_j F_{Norm}^j N_{CMUL}^j}{\sum_j F_{Norm}^j N_{CMUL}^j N_{MB}^{i,j} / N_{MB}^j} \times \frac{1}{\epsilon^{MB}} \quad (4.17)$$

Here, we have written only one correction factor ϵ^{MB} which includes all the type of corrections. As soon as $N_{MB}^{i,j}/N_{MB}^j$ vary with run number, Eq. 4.10 and

Eq. 4.17 are not identical. The only difference between Eq. 4.10 and Eq. 4.17 are the factors $\frac{\sum_j F_{\text{Norm}}^j N_{\text{CMUL}}^j}{\sum_j F_{\text{Norm}}^j N_{\text{CMUL}}^j N_{\text{MB}}^{i,j}/N_{\text{MB}}^j}$ and $\frac{N_{\text{MB}}^{\text{equiv}}}{N_{\text{MB}}^{\text{equiv},i}}$. Therefore, it is worth comparing the values of these quantity in different multiplicity bins.

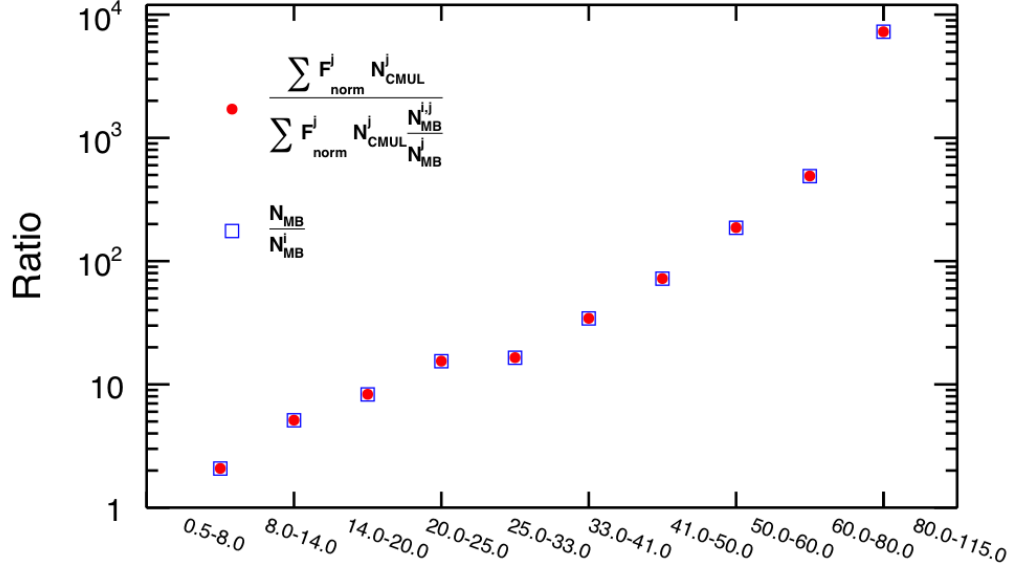


Figure 4.5. Comparison of two factors (from Eq. 4.10 and Eq. 4.17) for relative yield calculation [116].

For the completeness, we have tabulated the F_{Norm} factor corresponding to different multiplicity bins and are shown in table. 4.1. It can be seen from Fig. 4.5 that there is no such difference between the two opted methods for the multiplicity calculation. The calculation has been repeated for all other periods as well and no difference is found. For further calculation of relative yield, the minimum bias sample will be used which is given as,

$$Y_{\text{rel}}^i = \frac{N_{J/\psi}^i}{N_{J/\psi}} \times \frac{N_{\text{MB}}}{N_{\text{MB}}^i} \times \frac{1}{\epsilon_{\text{INEL}>0}^{\text{MB}}} \quad (4.18)$$

F_{Norm} factor in multiplicity bins for LHC 16p periods	
Multiplicity Class	F_{Norm}-factor
Integrated	2545.57 ± 0.07
1.0 - 8.0	7065.67 ± 0.206923
8.0 - 14.0	2910.2 ± 0.0891149
15.0 - 20.0	1798.13 ± 0.057543
21.0 - 25.0	1304.21 ± 0.063627
26.0 - 33.0	992.246 ± 0.035365
34.0 - 41.0	756.245 ± 0.033216
42.0 - 50.0	600.75 ± 0.0369103
51.0 - 60.0	486.173 ± 0.055358
61.0 - 80.0	398.625 ± 0.099896
81.0 - 115.0	300.721 ± 0.982639

Table 4.1. Normalization factor in different multiplicity bins.

4.3 J/ψ signal extraction

The J/ψ yields are extracted starting from the opposite sign invariant mass spectra in the range $2.3 < m_{\mu^+\mu^-} \text{ GeV}/c^2 < 5.5$ and $2.0 < m_{\mu^+\mu^-} \text{ GeV}/c^2 < 5.2$, fitting them with different phenomenological functions, which describe the signal of J/ψ and $\psi(2S)$ and the background. First, the signal has been extracted for integrated multiplicity and integrated p_T . Then, it is divided into 11 multiplicity bins and in each multiplicity bin the signal has been extracted following the same procedure. The functions used to characterize the J/ψ signal consist of a Gaussian core with power-law tails added on either side of the mean of the peak. The deviation from Gaussian function comes from the following contribution: (1) multiple coulomb scatterings in the front absorber and in the tracking chambers. These phenomena increase the energy loss and contribute to the left tail. (2) radiative decays and energy loss in the front absorber contributes to left tail as well. (3) The alignment of the detector. This effect is symmetric and contributes to both left and right tails. For the current analysis,

two signal functions have been used: (1) Extended Crystal ball function (CB2)¹ and (2) NA60 function². The mathematical form of CB2 and NA60 function are given in the appendix section 8.11. The tail parameters of CB2 function (α, n, α', n') are obtained from the data which is used for 13 TeV cross section analysis [122] and from the simulation. Whereas, the tail parameters of NA60 function (p7, p8, p9, p10) has been used only from the simulation. The function used to parametrize the background are: (1) Variable width Gaussian function (VWG) (Ref. 8.11) and (2) $Pol4 \times Exponential$.

Since, the signal to background ratio in $\psi(2S)$ region is too small, the $\psi(2S)$ mass (m_ψ) and width (σ_ψ) is fixed to that of J/ψ in the following way:

$$m_{\psi(2S)} = m_{J/\psi} + (m_{\psi(2S)}^{PDG} - m_{J/\psi}^{PDG}), \quad (4.19)$$

where PDG denotes the values given in the Particle Data Group [18].

$$\sigma_{\psi(2S)} = \sigma_{J/\psi}^{FIT} \times \frac{\sigma_{\psi(2S)}^{MC}}{\sigma_{J/\psi}^{MC}} \quad (4.20)$$

To extract the width of $\psi(2S)$ and J/ψ , we have fitted the MC mass spectra with CB2 and NA60 function, which is shown in Fig. 4.6 and Fig. 4.7.

¹The function was christened after the Crystal Ball detector, originally located at the SPEAR in SLAC. The detector was designed to study charmonia and was the one to discover the η_c resonance [123].

²Named after the NA60 experiment at the SPS in CERN [124]. The experiment studied “prompt dimuons and charm production with proton and heavy ion beams.”

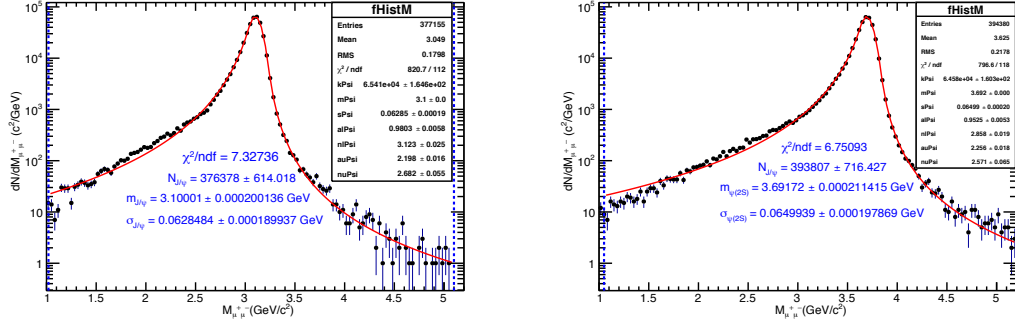


Figure 4.6. Fit of the J/ψ (left) and $\psi(2S)$ (right) MC mass spectra at $\sqrt{s} = 13$ TeV using an extended Crystal Ball function (CB2) with all parameters free [116].

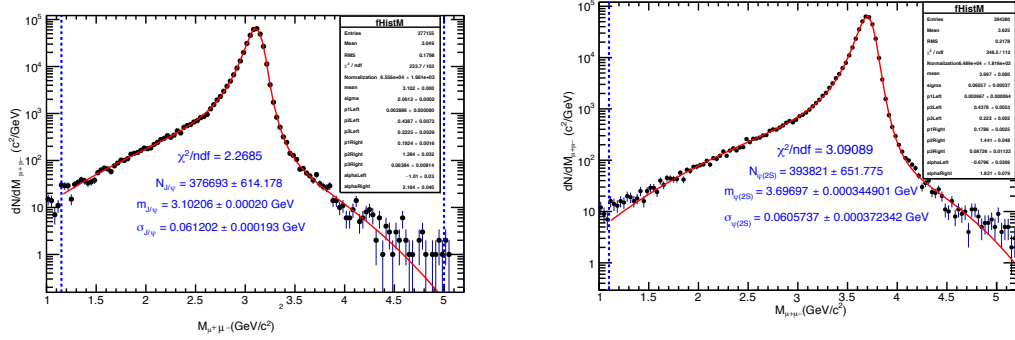


Figure 4.7. Fit of the J/ψ (left) and $\psi(2S)$ (right) MC mass spectra at $\sqrt{s} = 13$ TeV using a NA60 function with all parameters free [116].

Using the above mentioned constraint, we have fitted the integrated invariant mass spectra using different signal and background functions. This is shown in the Fig. 4.8. Keeping in mind the previous analyses [114, 117, 118], we assume that the signal shape for the multiplicity bin in pp collisions is also same. Thus the tails as well as the ratio of width ($\psi(2S)$ to J/ψ) in multiplicity bin is same as the integrated spectrum. In the multiplicity bins (N_{trk}^{corr}), the fitting is performed using different signal and background functions in different fitting ranges. The detailed about it will be discussed in the systematic analysis section 4.3.1. The example plots for in multiplicity (N_{trk}^{corr}) bins for the combination CB2+VWG, using the tail parameter of $\sqrt{s} = 13$ TeV cross section

analysis in the fitting range 2.3 to 5.5 GeV/c^2 , are shown in Fig. 4.9. In this section, we have shown the example figures of signal extraction for J/ψ in corrected multiplicity bins using maximum as reference. A comparative study has been done for signal extraction, taking minimum and maximum as reference and is discussed the section 4.3.2.

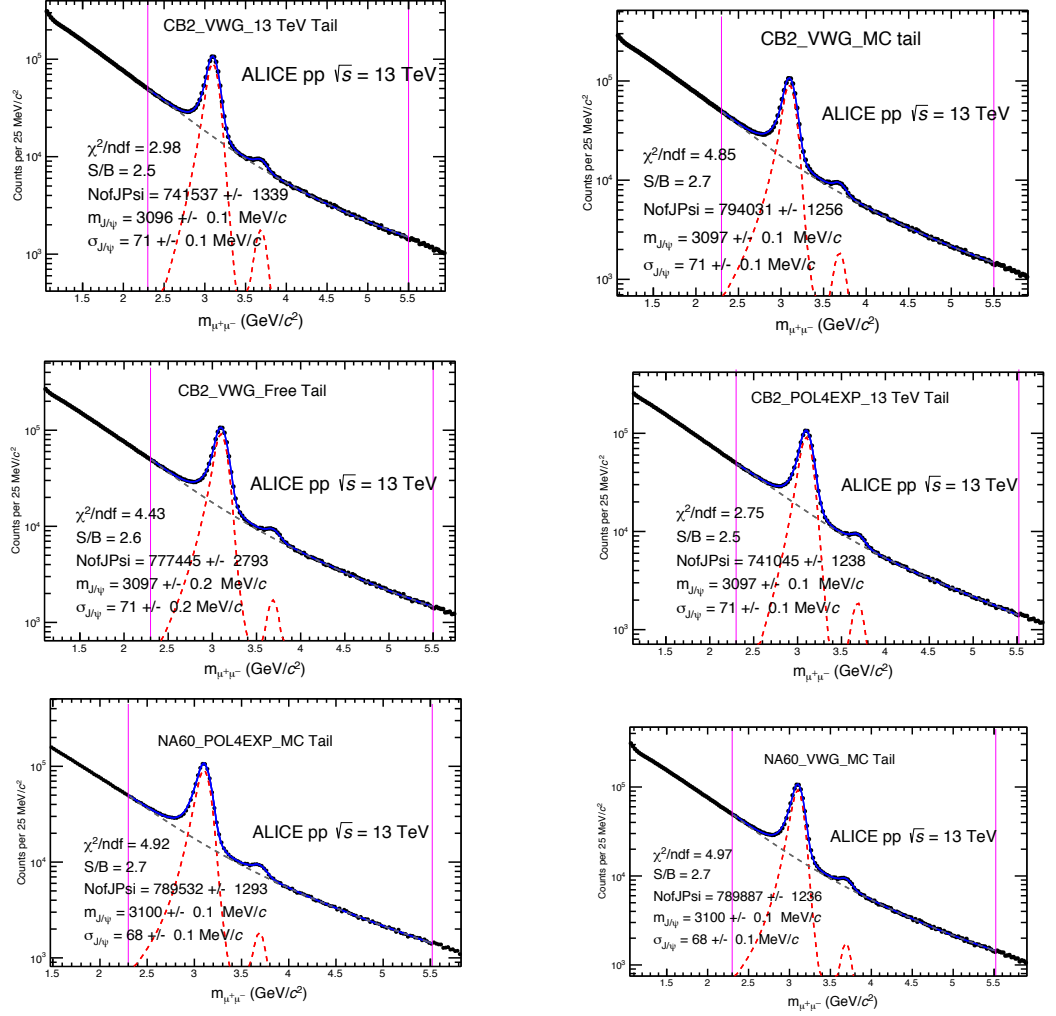


Figure 4.8. Example of signal extractions for the integrated invariant mass spectra using different signal and background function in the range $2.3 < m_{\mu^+\mu^-}(\text{GeV}/c^2) < 5.5$. The signal is extracted in 3σ region [116].

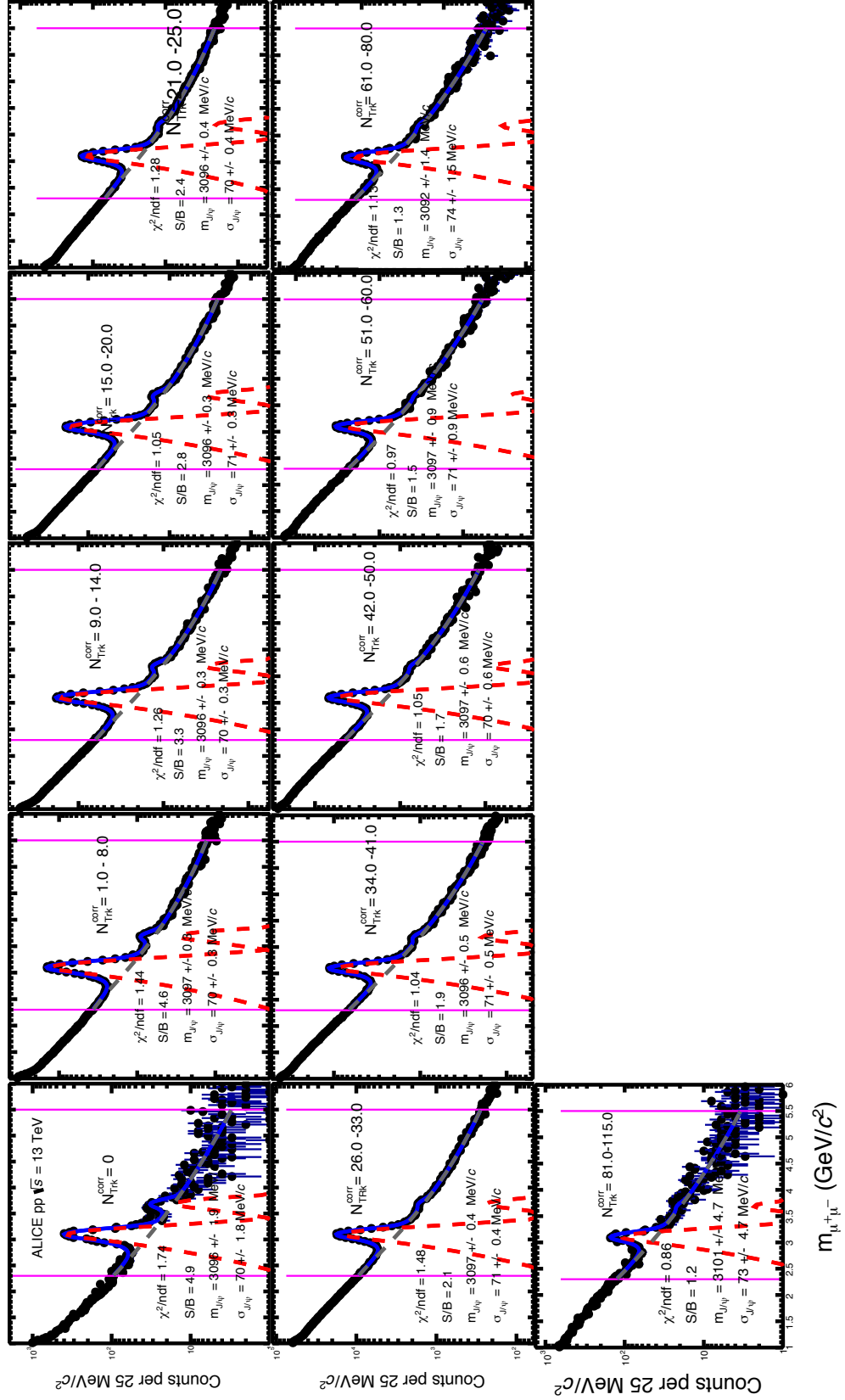


Figure 4.9. Example of signal extractions in different multiplicity bins using CB2+VWG function in the range $2.3 < m_{\mu^+\mu^-}(\text{GeV}/c^2) < 5.5$ [116].

As can be observed from the Fig. 4.10, the obtained values of mass of J/ψ is stable along the multiplicity bins and is around the PDG value. The width is also consistent along multiplicity and its value is around 71 MeV/ c^2 . For all the combinations of fitting the χ^2/ndf values lie below 3.0 and in most of the cases it is around 1. The quality of fitting can be seen from Fig.4.9 for CB2+VWG. For the present analysis, the multiplicity bin (115, 160) is excluded because the signal to background ratio is around -1.0, in all the combinations of fits which is unphysical. We can not merge this multiplicity bin with the previous bin because of the fact that the N_{Trk}^{corr} value in MC extends up to $N_{Trk}^{corr} = 115$. Therefore, because of the limitation in the data, we cannot extend the measurement to a region where we do not have statistics. We strictly constrain the multiplicity bin up to 115. Again, although there are significant number of J/ψ for the multiplicity bin $N_{trk}^{corr} = -0.5$ to 0.5, it is excluded because in MC we measure the charged-particle from 1 ($N_{ch} > 1$). Also, the bin 0 is hard to correct for detector effect and event selection when we measure 0.

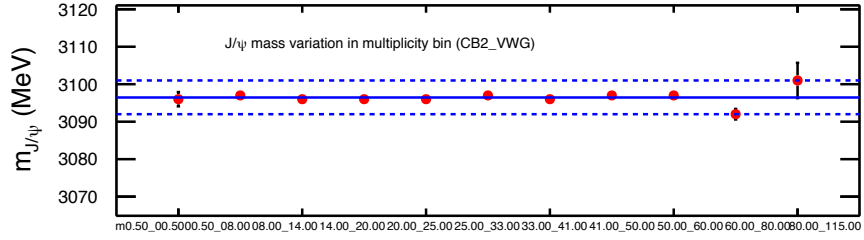


Figure 4.10. J/ψ mass variation along the multiplicity bins [116].

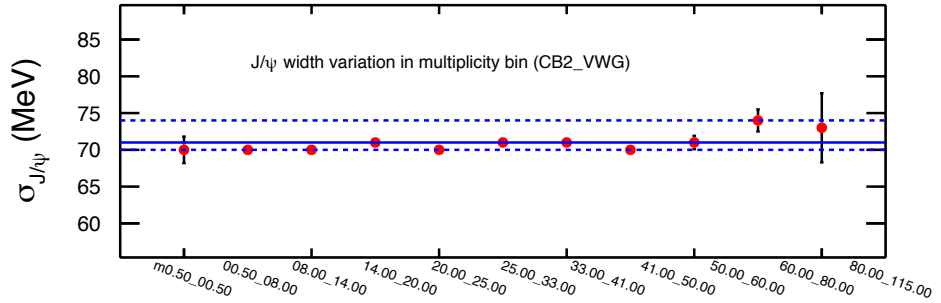


Figure 4.11. J/ψ width variation along the multiplicity bins [116].

4.3.1 Systematic uncertainty in signal extraction

The signal extraction procedure is performed using 12 tests, due to 2 signal functions, 2 background shapes, 2 invariant mass fitting ranges and 2 sets of tails for the CB2. These are listed below:

- Two Signal function: Extended Crystal Ball (CB2) and the phenomenological function of NA60
- Two Background function: Variable Width Gaussian function and $Exponential \times Polynomial$
- Two Mass ranges: $2.3 < m_{\mu^+\mu^-}(\text{GeV}/c^2) < 5.5$ and $2.0 < m_{\mu^+\mu^-}(\text{GeV}/c^2) < 5.2$
- Three set of tails for CB2: Tails from the $\sqrt{s} = 13$ TeV cross section analysis (obtained from data), tails from MC and free tails where tails of $\psi(2S)$ is tight from that of J/ψ
(For free tail we have let the tails free in our fit)
- The tails of NA60 is taken from MC

In total, performing all combinations listed above would result in 12 tests in integrated over multiplicity bin as well as in each multiplicity slice. To be noted here, for the test performed for free tails, the tail parameters obtained in integrated multiplicity is used for multiplicity bins due to the lack of statistics. The linear average of the corresponding statistical uncertainties in each test is assigned as the statistical uncertainty for each bin and the RMS of the distribution of the 12 tests is used as the corresponding systematic uncertainty. We have fixed the width of $\psi(2S)$ signal with the J/ψ one as discussed earlier. From the earlier study [125], it is found that it contributes around 5% to the systematic uncertainty. So, a systematics of 5% has been added to the signal extraction in all cases and has negligible effect. Finally, The mean value, statistical uncertainty and systematic uncertainty of signal are calculated in each multiplicity bin as well as in integrated multiplicity bin using the same

method. For completeness, we have listed below the formulas used for statistical and systematic uncertainty calculation:

$$\sigma_{\langle X \rangle}^{syst} = \sqrt{\frac{\sum_{i=1}^{n_{tests}} (X_i - \langle X \rangle)^2}{n_{tests}}} \quad (4.21)$$

$$\sigma_{\langle X \rangle}^{stat} = \frac{1}{n_{tests}} \sum_{i=1}^{n_{tests}} \sigma_{X_i} \quad (4.22)$$

Where, X_i is the quantity obtained in each test, $\langle X \rangle$ is the mean of X_i and σ_{X_i} is the statistical error in each test.

Fig.4.12 and Fig.4.13 show the results of the 12 fits to the multiplicity-integrated invariant mass distribution. The abbreviation of X-axis, for example "CB2VWG.2.3–5.5_Tail13TeV" means "*Signal + Background + Fitting range + Tail*". The total number of signal counts as well as the corresponding statistical and systematic uncertainties are also shown in the figures. Two populations of values are obtained located at the upper and lower limits of the 1σ systematic uncertainty. It can be observed from Fig.4.4, the difference is arising because of different signal functions and does not depend much on the background function. There is a significant difference in number of signal counted for different set of tail parameters. Same difference has been observed for cross section analysis as well. To understand the effect, an extensive study has been performed in cross section analysis of J/ψ for pp collisions at $\sqrt{s} = 13$ TeV [122]. The same systematic difference is also visible for all multiplicity bins, as illustrated in section. 8.12 and section. 8.15 taking maximum and minimum as reference. The same pattern of systematic difference is observed for all multiplicity bins, as illustrated in section. 8.12 and 8.15. We have provided the χ^2/ndf and J/ψ width versus tests in the section. 8.13, section. 8.16 and section. 8.14, 8.17 respectively to validate the tests.

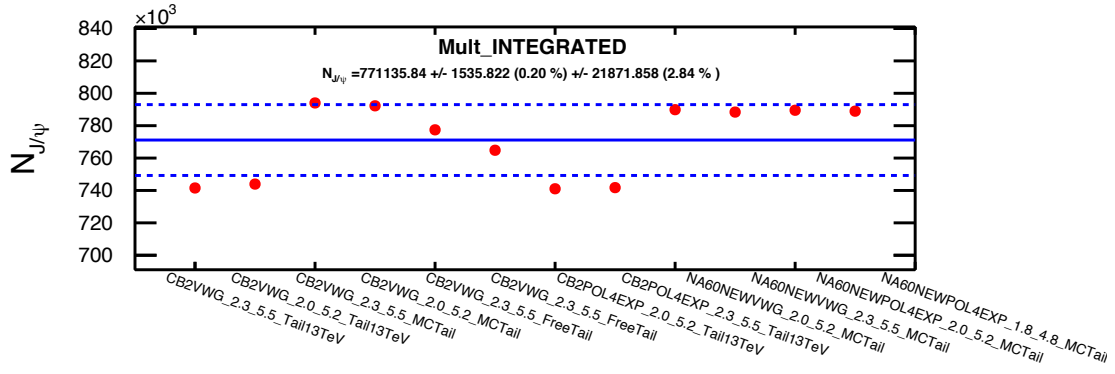


Figure 4.12. J/ψ yield in different set of tests for integrated multiplicity taking maximum as reference [116].

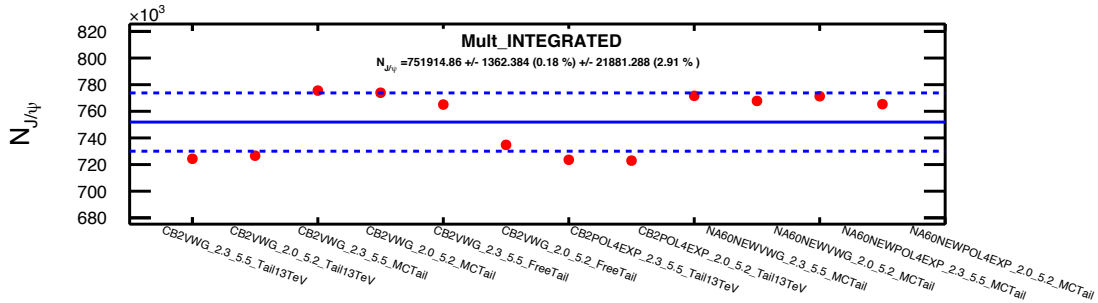


Figure 4.13. J/ψ yield in different set of tests for integrated multiplicity taking minimum as reference [116].

From this systematic uncertainty analysis, we can conclude the following point for the integrated as well as for multiplicity bins:

- Less than 1% difference is found, when we use different fitting ranges.
- The usage of different background function: VWG and $EXP \times POL4$ give negligible effect to the systematics.
- The maximum deviation in signal is coming from different sets of tail parameters. It is also quoted in Ref. [122].
- A deviation of around 1% in signal arises due to the use of different signal functions CB2 and NA60.

- Combination of all the test results give around 2-3% systematic difference.

We have tabulated the mean value, statistical uncertainty and systematic uncertainty of signal taking minimum as well as maximum as reference and this can be seen from table. 4.2. To have a direct comparison, we have chosen same binning for minimum and maximum as references.

Number of J/ψ along with the statistical and systematic error							
Bins		Ref.: Maximum			Ref.: Minimum		
Mult-Bin (Ref:Max)	Mult-Bin (Ref:Min)	$N_{J/\psi}$	Stat. Error	Syst. Error	$N_{J/\psi}$	Stat. Error	Syst. Error
Integrated	Integrated	771136	1536(0.20 %)	21872 (2.84 %)	751915	1362 (0.18%)	21881 (2.91 %)
0	0	3006	72 (2.40 %)	70 (2.35 %)	7149	109 (1.53 %)	197 (2.76 %)
1.0 - 8.0	1.0 - 5.0	109250	435(0.40 %)	3065(2.81 %)	90793	402 (0.44 %)	2531 (2.79 %)
9.0 - 14.0	6.0 -10.0	134783	516(0.38 %)	3693(2.74 %)	161671	558 (0.35 %)	4594 (2.84 %)
15.0 - 20.0	11.0-14.0	138667	536(0.39 %)	3908(2.82 %)	128672	510 (0.40 %)	3683 (2.86 %)
21.0 - 25.0	15.0-17.0	102139	484(0.47 %)	3034(2.97 %)	85210	437 (0.51 %)	2462 (2.89 %)
26.0 - 33.0	18.0-23.0	125379	553(0.44 %)	3601(2.87 %)	131174	582 (0.44 %)	3861 (2.94 %)
34.0 - 41.0	24.0-28.0	78618	479(0.61 %)	2287(2.91 %)	67552	421 (0.62 %)	1959 (2.90 %)
42.0 - 50.0	29.0-34.0	46047	373(0.81 %)	1348(2.93 %)	44610	344 (0.77 %)	1314 (2.95 %)
51.0 - 60.0	35.0-42.0	21833	247(1.13 %)	641(2.94 %)	24703	263 (1.07 %)	732 (2.96 %)
61.0 - 80.0	43.0-54.0	10485	189(1.81 %)	317(3.02 %)	8655	171 (1.98 %)	270(3.13 %)
81.0 - 115.0	55.0-83.0	953	59(6.21 %)	24 (2.53 %)	1211	65 (5.41 %)	35(2.89 %)

Table 4.2. Number of J/ψ along with the statistical and systematic errors in different multiplicity bins [116].

Here, we have observed that, the sum of number of J/ψ in each multiplicity bins, also the statistical and systematic errors by quadrature is consistent with the integrated value within uncertainties. In table.4.2, we have omitted the bin (-1.5 - 0.5) and (-0.5 - 0.5), to be consistent with N_{ch} measurement. The quoted integrated value of number of J/ψ is well consistent with the other analyses.

4.3.2 Relative J/ψ yield as a function of multiplicity

The self normalized J/ψ yield is defined as [114, 117–119],

$$\frac{\frac{dN_{J/\psi}}{dy}}{\langle \frac{dN_{J/\psi}}{dy} \rangle} = \frac{N_{J/\psi}^i}{N_{J/\psi}^{tot}} \times \frac{N_{Evt}^{tot}}{N_{Evt}^i} \times \frac{1}{\epsilon_{INEL>0}^{MB}} \times \frac{1}{\epsilon_{vtx}}, \quad (4.23)$$

where $N_{J/\psi}^i$ and N_{Evt}^i are the number of J/ψ and number of events in the i^{th} multiplicity bin, and $N_{J/\psi}^{tot}$ and N_{Evt}^{tot} are the number of J/ψ and number of events in the minimum bias sample corresponding to analyzed di-muon trigger sample. $\epsilon_{INEL>0}^{MB}$ is the efficiency of the MB trigger to select $INEL > 0$ collisions. ϵ_{vtx} is the efficiency of the vertex finding algorithm. In the current analysis, we have used $INEL > 0$ sample, which is defined as inelastic events with at least one physical primary charged-particle within $|\eta| < 1$. Taking care of all kind of corrections associated with the calculation, the relative J/ψ yield can be written as,

$$\frac{\frac{dN_{J/\psi}}{dy}}{\langle \frac{dN_{J/\psi}}{dy} \rangle} = \frac{N_{J/\psi}^i}{N_{J/\psi}^{tot}} \times \frac{F_{Norm}^{tot}}{F_{Norm}^i} \times \frac{N_{MUL}^{tot}}{N_{MUL}^i} \times \frac{\epsilon^{MB,i}}{\epsilon^{MB}} \times \frac{\epsilon^{J/\psi}}{\epsilon^{J/\psi,i}} \quad (4.24)$$

The meaning of different variables of Eq. 4.24 are listed below,

- $N_{J/\psi}^{tot}$ = total number of J/ψ for the integrated multiplicity
- $N_{J/\psi}^i$ = number of J/ψ for the i^{th} multiplicity bin
- F_{Norm}^{tot} = normalization factor corresponding to the integrated multiplicity
- F_{Norm}^i = normalization factor corresponding to the i^{th} multiplicity bin
- ϵ^{MB} = the multiplicity integrated corrections for minimum bias events
- $\epsilon^{MB,i}$ = the corrections in multiplicity bin i for minimum bias events
- $\epsilon^{J/\psi}$ = the multiplicity integrated corrections for events with a J/ψ
- $\epsilon^{J/\psi,i}$ = the corrections in multiplicity bin i for events with a J/ψ

The four efficiency terms, each have several contributions from different sources are,

- $\epsilon_{INEL>0}$ = the minimum bias trigger efficiency for $INEL > 0$ events

- $\epsilon_{vtx,range}$ = the efficiency of the vertex range cuts
- $\epsilon_{vtx,QA}$ = the efficiency of the vertex QA cuts
- ϵ_{pu} = the efficiency of the pile-up rejection

The Eq. 4.24 has several correction factors. Many of them cancel out or are unity. Finally, the equation will remain with the following corrections factors, which we have already sstimated;

- **Multiplicity integrated corrections for MB event ($INEL > 0$) (ϵ^{MB}):**

Discussed in section. 3.3.2 and the value is $\epsilon_{MB} = 0.94$ for both minimum as well as maximum as references.

- **Corrections in multiplicity bin“i” for MB events ($\epsilon^{MB,i}$):**

Tabulated in section. 3.3.2. The values are provided in multiplicity bins for both minimum as well as maximum as reference.

- **The efficiency of the vertex QA cuts for J/ψ and MB events ($\epsilon_{vtx,QA}^{J/\psi} / \epsilon_{vtx,QA}^{MB}$):**

The calculation of this value is mentioned in section.3.1.2 and the value is,

$$\epsilon_{vtx,QA}^{J/\psi} / \epsilon_{vtx,QA}^{MB} = 1.03737 \pm 0.00288$$

- **The efficiency of pile-up rejection (ϵ_{pu}):**

$\epsilon_{pu} \approx 1$ has been found for all the multiplicity bins. The calculation has been shown in section. 3.3.5.

Considering all the above factors and discussion in section. 4.2, Eq. 4.24 can be modified as,

$$\frac{\frac{dN_{J/\psi}}{dy}}{\langle \frac{dN_{J/\psi}}{dy} \rangle} = \frac{N_{J/\psi}^{bin}}{N_{J/\psi}^{integrated}} \times \frac{N_{CINT7}^{total}}{N_{CINT7}^{bin}} \times \frac{\epsilon^{INEL>0,i}}{\epsilon^{INEL>0}} \times \frac{\epsilon_{vtx,QA}^{J/\psi}}{\epsilon_{vtx,QA}^{MB}} \times \frac{1}{\epsilon^{INEL=0}} \times \epsilon_{pu} \quad (4.25)$$

Plugging all the correction factors along with the extracted signal taking maximum as reference, we have plotted self-normalized J/ψ yield as a function of self-normalized charged-particle density and is shown in the Fig. 4.14. We have also performed the similar kind of study taking minimum as reference and the comparison between both are presented in Fig. 4.15. It can be seen from the figure that the relative J/ψ yield as a function of relative charged-particle multiplicity is almost independent of choice of reference for the Z_{vtx} correction. The little difference between them arises because of difference in N_{ch} value (X-axis). The difference between the two methods (maximum and minimum as reference) will be assigned as systematic uncertainty for the final calculation. The ratio between the results taking maximum and minimum as references is shown in Fig. 4.16, where we assume relative J/ψ are evaluated at the same X-axis (N_{ch}). We assign the difference in relative J/ψ yield as systematic uncertainty following the same procedure as in Ref. [118]. Following are the assumptions taken for the calculation,

- It is assumed that the results for maximum and minimum are at the same $dN_{ch}/d\eta/\langle dN_{ch}/d\eta \rangle$. The difference between two are neglected.
- The relative difference between maximum and minimum are calculated as,

$$\Delta R_{J/\psi} = \frac{|(dN_{J/\psi}/dy / \langle dN_{J/\psi}/dy \rangle)^{max} - (dN_{J/\psi}/dy / \langle dN_{J/\psi}/dy \rangle)^{min}|}{(dN_{J/\psi}/dy / \langle dN_{J/\psi}/dy \rangle)^{max}} \quad (4.26)$$

We have neglected the statistical uncertainty (and are correlated between two distributions), which leads to increase in uncertainty of the quantity $\Delta R_{J/\psi}$.

- The uncertainty is taken as Gaussian and is calculated as

$$\sigma_{equal.} = \Delta R_{J/\psi} / \sqrt{12} \quad (4.27)$$

Systematic uncertainty from vertex equalization	
$\frac{dN_{ch}/d\eta}{\langle dN_{ch}/d\eta \rangle}$	Sys. Uncert($\sigma_{equal.}$)
0.40	0.34%
1.00	0.37%
1.53	0.46%
2.00	0.37%
2.52	0.21%
3.18	0.52%
3.86	0.76%
4.61	0.34%
5.57	1.44%
7.17	1.98%

Table 4.3. Systematic uncertainty from vertex equalization using minimum and maximum as reference.

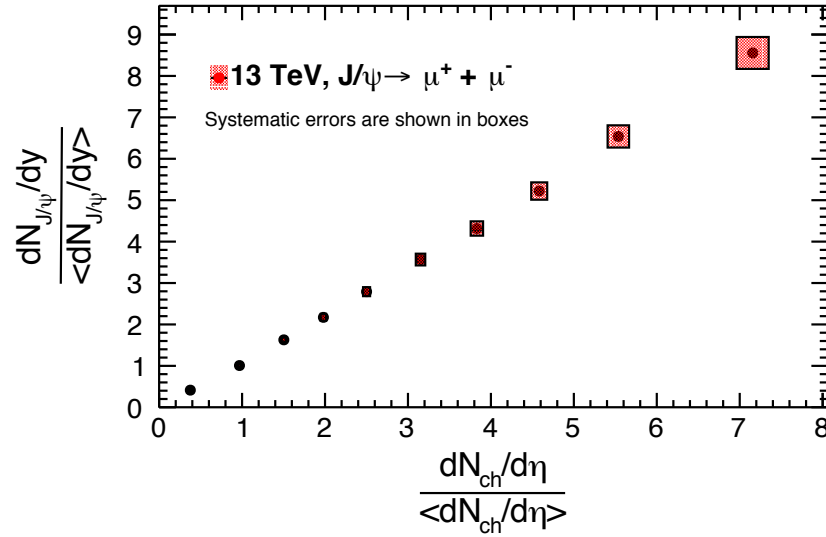


Figure 4.14. Self-normalized J/ψ yield as a function of self-normalized charged-particle density for pp collisions at $\sqrt{s} = 13$ TeV in forward rapidity. Here, the charged-particle multiplicity is determined using maximum as reference for Z_{vtx} equalization [116].

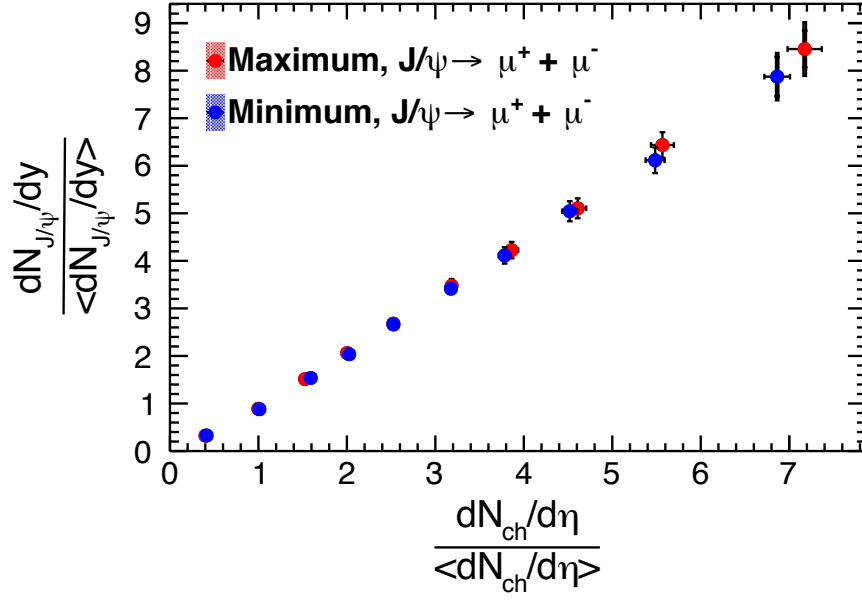


Figure 4.15. Comparison of Self-normalized J/ψ yield as a function of self-normalized charged-particle density for pp collisions at $\sqrt{s} = 13$ TeV in forward rapidity taking maximum and minimum as reference for Z_{vtx} equalization [116].

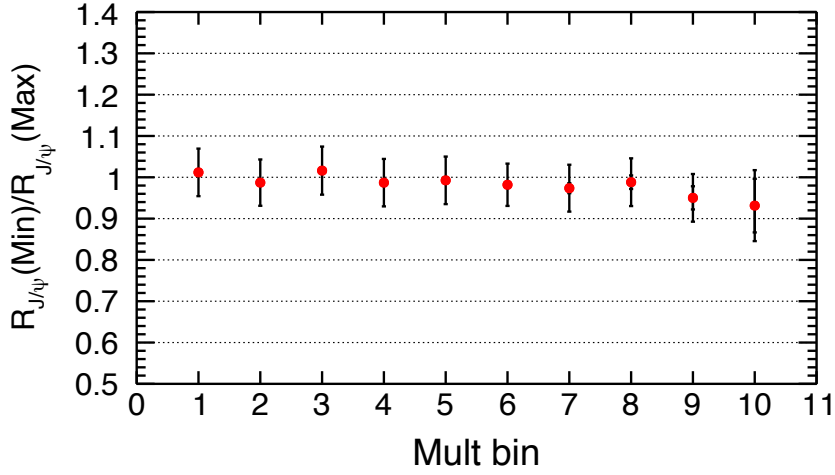


Figure 4.16. Ratio of Self-normalized J/ψ yields (Min. to Max) assuming both are evaluated at the same N_{ch} bin (X-axis) for maximum and minimum as reference for Z_{vtx} equalization [116].

Summary of Systematic Uncertainties			
$\frac{dN_{ch}/d\eta}{\langle dN_{ch}/d\eta \rangle}$		$\frac{dN_{J/\psi}/dy}{\langle dN_{J/\psi}/dy \rangle}$	
Sources	Max. % of contribution	Sources	Max. % of contribution
From different sources as discussed in Sec. 3.3.6	2.7%	From different sources as discussed in Sec. 4.3.1	4.56%
From non-linearity	6.06%	From Z_{vtx} equalization	1.98%

Table 4.4. Summary table of systematic uncertainties.

4.4 J/ψ Mean transverse momentum analysis

In this section, we have described the analysis of mean transverse momentum of J/ψ ($\langle p_T^{J/\psi} \rangle$) and its multiplicity dependence study. For this analysis, a technique different from the traditional method of extracting $\langle p_T^{J/\psi} \rangle$ from p_T spectra has been opted [114, 118]. We have constructed di-muon mean transverse momentum invariant mass spectrum ($\langle p_T^{\mu^+\mu^-} \rangle(m_{\mu^+\mu^-})$) and fit to extract the J/ψ $\langle p_T \rangle$. Using this method, one can suitably extract $\langle p_T \rangle$, when we have less number of signal. The $\langle p_T \rangle$ extracted from this method is well consistent with $\langle p_T \rangle$ extracted from the traditional method [148]. The fitting function used in this extraction is a phenomenological one, based on weighting the $\langle p_T \rangle$ of each particle entering in the spectrum (J/ψ and $\psi(2S)$).

$$\begin{aligned}
\langle p_T \rangle^{\mu^+\mu^-}(m_{\mu^+\mu^-}) &= \alpha^{J/\psi}(m_{\mu^+\mu^-}) \times \langle p_T^{J/\psi} \rangle(m_{\mu^+\mu^-}) + \alpha^{\psi(2S)}(m_{\mu^+\mu^-}) \times \langle p_T^{\psi(2S)} \rangle \\
&+ (1 - \alpha^{J/\psi}(m_{\mu^+\mu^-}) - \alpha^{\psi(2S)}(m_{\mu^+\mu^-})) \times \langle p_T \rangle^{\text{bkg}}
\end{aligned} \tag{4.28}$$

$$\text{where, } \alpha(m_{\mu^+\mu^-}) = \frac{S(m_{\mu^+\mu^-})}{(S^{J/\psi}(m_{\mu^+\mu^-}) + S^{\psi(2S)}(m_{\mu^+\mu^-}) + B(m_{\mu^+\mu^-}))}.$$

The signal (S) and background (B) dependence on the di-muon invariant mass is extracted from the corrected invariant mass spectrum fits. The J/ψ and $\psi(2S)$ average transverse momenta, $\langle p_T^{J/\psi} \rangle$ and $\langle p_T^{\psi(2S)} \rangle$, respectively, are

fit parameters assumed to be independent of the invariant mass, while the background one, $\langle p_T \rangle^{\text{bkg}}$, is parameterized with a second order polynomial function.

It should be noted that the $\langle p_T \rangle$ value obtained in this way is not yet corrected by acceptance and efficiency ($A \times \epsilon$). Since, the J/ψ $A \times \epsilon$ depends strongly on p_T , the obtained value will be overestimated, as the muon spectrometer is less efficient for low- p_T values.

The di-muon $\langle p_T \rangle$ invariant mass spectrum is corrected as following way;

$$\langle p_T^{\mu^+\mu^-} \rangle_{A \times \epsilon}(m_{\mu^+\mu^-}^i) = \frac{1}{n_i^{\text{eff}}} \sum_{j=1}^{n_i} \frac{p_T^j}{A \times \epsilon(p_T^j, y^j)} \quad (4.29)$$

where,

$$n_i^{\text{eff}} = \sum_{j=1}^{n_i} \frac{1}{A \times \epsilon(p_T^j, y^j)} \quad (4.30)$$

y^j and p_T^j are rapidity and transverse momentum of the j^{th} pair.

4.4.1 Acceptance and efficiency calculation

The dimuon spectrum needed to be corrected by the 2D acceptance and efficiency $A \times \epsilon(p_T, y)$ of the spectrometer. The acceptance and efficiency ($A \times \epsilon$) have been determined by simulating J/ψ signal using p_T and y input distributions from cross section analysis performed using 2015 data sample [122]. The signals were generated within a wider rapidity range ($2.0 \leq y \leq 4.5$) in order to account for the edge effects of the acceptance region. The $A \times \epsilon$ calculation has been performed on a run-by-run basis with a realistic MC simulation. It includes the experimental conditions of the Muon Spectrometer from Offline Calibration Data Base (OCDB). Around 10 million events were generated for each period (LHC 16h, 16j, 16k, 16o, 16p) weighted by the unlike sign dimuon trigger per run. An additional weight has been applied, when we merge all

the analysed periods to produce a single $A \times \epsilon$ map. The $A \times \epsilon$ factor was determined as the ratio of the number of reconstructed signals over the generated events in the muon acceptance. For the completeness, we have shown the reconstructed and generated p_T and y distribution and their ratio in Fig. 4.17 and Fig.4.18 for LHC 16h period. J/ψ 2D $A \times \epsilon$ corrections in (p_T, y) bins have been computed. The results for these corrections are shown in Fig.4.19 for 2016 (LHC 16h + 16j + 16k + 16o+16p) data as a 2D $A \times \epsilon$ map.

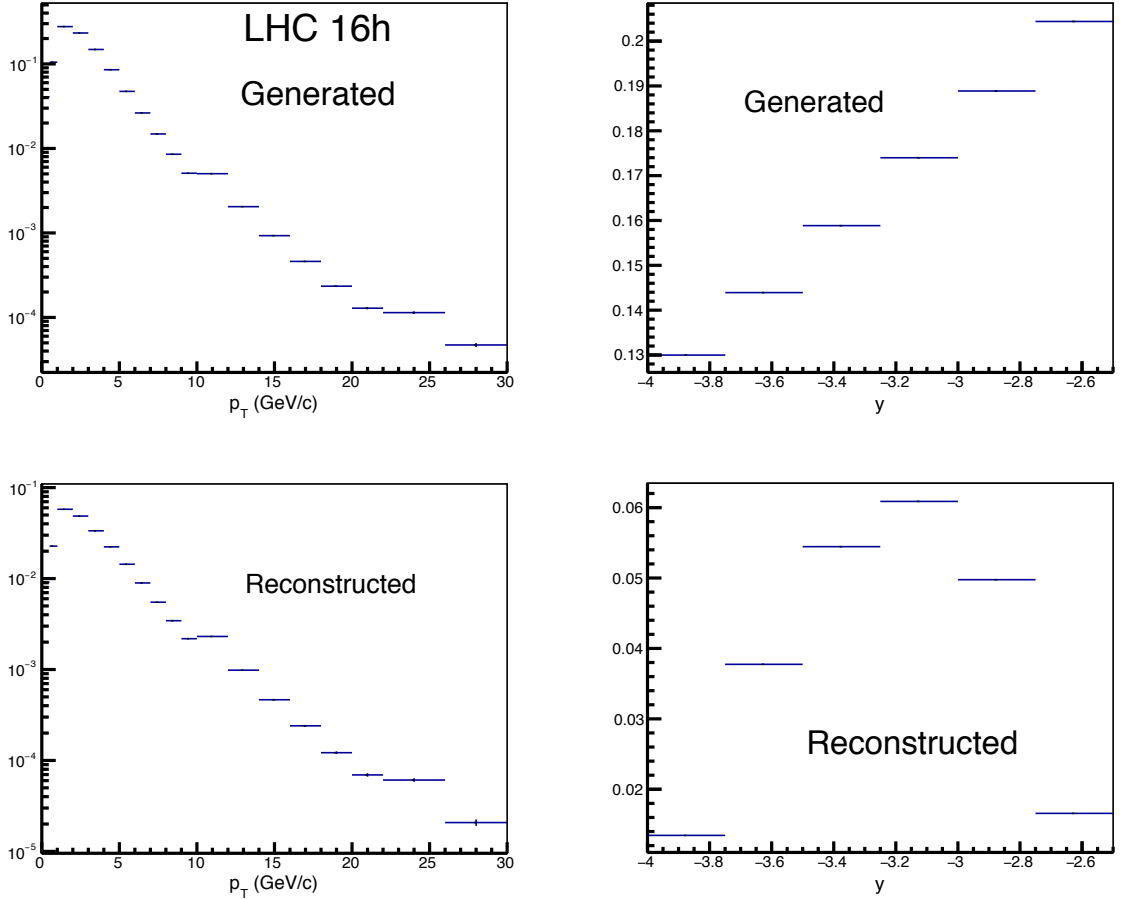


Figure 4.17. Example plots for generated and reconstructed p_T and y spectra in pp collisions at $\sqrt{s} = 13$ TeV for LHC 16h period [116].

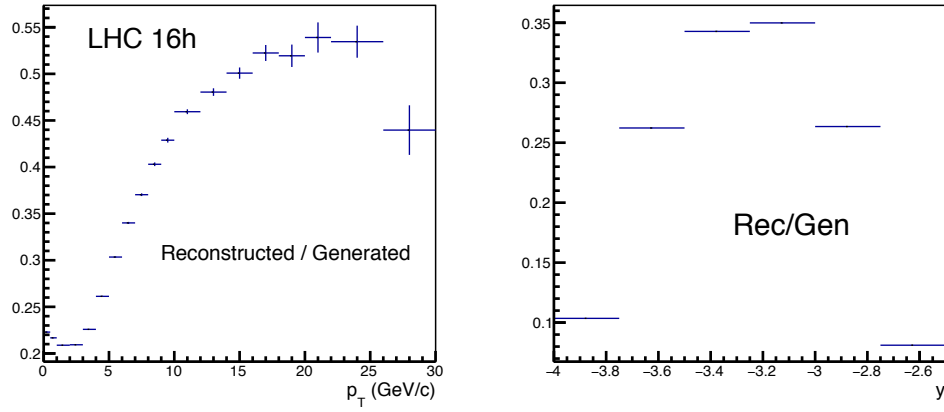


Figure 4.18. Ratio of reconstructed to generated p_T and y spectra in pp collisions at $\sqrt{s} = 13$ TeV for LHC 16h period [116].

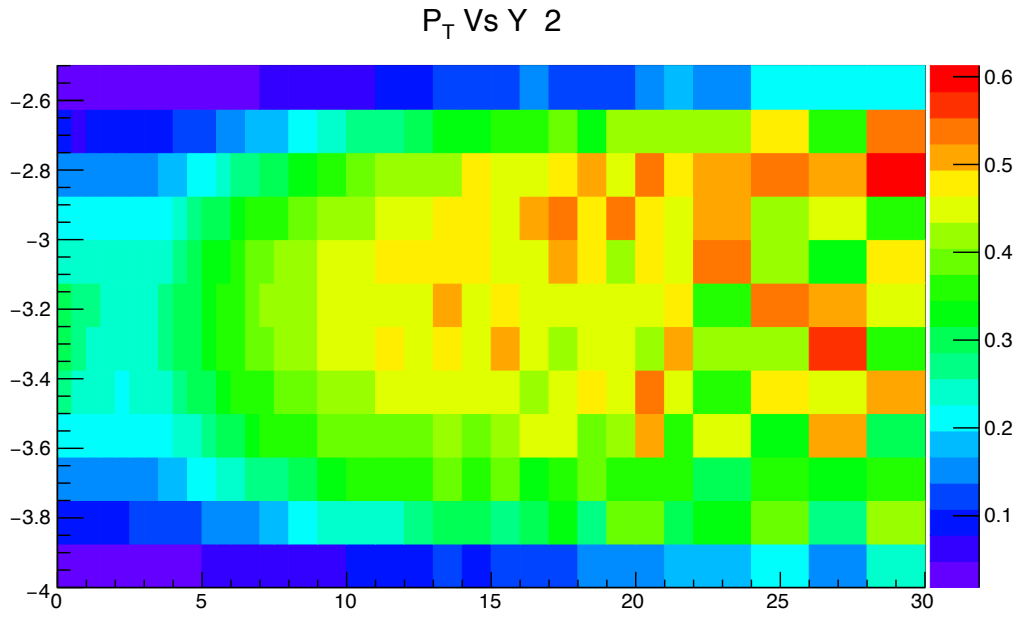


Figure 4.19. 2D $A \times \epsilon(p_T, y)$ map of the Muon Spectrometer in pp at $\sqrt{s} = 13$ TeV for 2016 data (LHC 16h + 16j + 16k + 16o + 16p) [116].

4.4.2 Mean transverse momentum extraction

To perform the $\langle p_T \rangle$ fitting procedure, all the signal and background parameters are fixed to those extracted from the corresponding invariant mass spectrum

in the integrated and multiplicity bins. Since, we assume that the signal does not vary with multiplicity, the tail parameters used in the signal extraction procedure are the same for the integrated and every multiplicity bin. The $\sigma_{J/\psi}$ ($\sigma_{\psi(2S)}$) and $m_{J/\psi}$ ($m_{\psi(2S)}$) are also supposed to be the same. Nevertheless, there are small variations from bin-to-bin which will be taken into account in the $\langle p_T \rangle$ fits by taking the values from corresponding result in each bin. Fig. 4.20 shows the fit results of $A \times \epsilon$ corrected invariant mass spectrum and the corresponding $\langle p_T \rangle$, for the fit combination “CB2 + VWG + POL2 + 13 TeV Tail”. We have also shown the fitting results for the extraction of $\langle p_T \rangle$ of J/ψ in each multiplicity bins in Fig. 4.21.

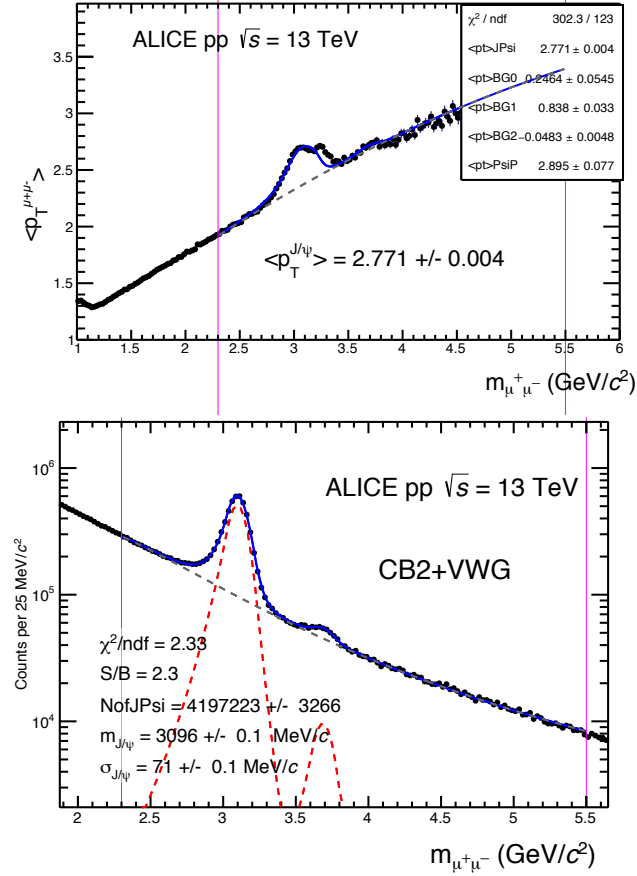


Figure 4.20. Fit to the multiplicity integrated, $A \times \epsilon$ corrected invariant mass spectrum in pp (top) and the corresponding $\langle p_T \rangle$ (bottom). The invariant mass spectrum is fitted with CB2 + VWG and tail parameters is taken from cross section analysis in pp collisions at $\sqrt{s} = 13$ TeV. The second order polynomial (POL2) function is taken as the background function ($\langle p_T \rangle^{bkg}$) [116].

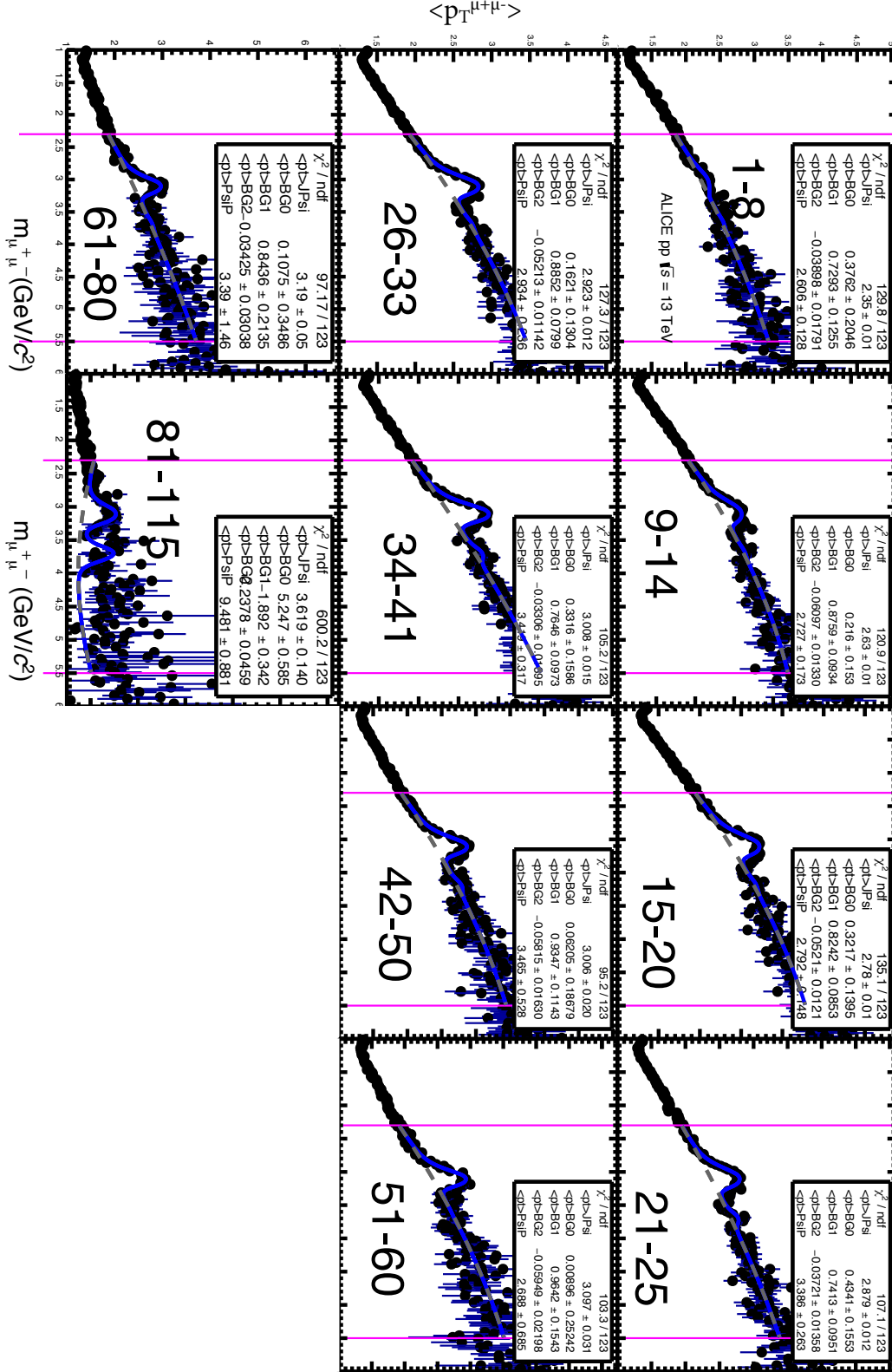


Figure 4.21. Example of $\langle p_T \rangle$ fit in the multiplicity bins for pp collisions at $\sqrt{s} = 13$ TeV using the fit combination "*CB2 + VWG + POL2 + 13 TeV Tail*" [116].

4.4.3 Cross check: Extraction of $\langle p_T^{J/\psi} \rangle$ from the p_T spectra

Using different combination of tests, we have extracted the $A \times \epsilon$ (using the same 2D map) corrected yield of J/ψ in p_T bins for the integrated multiplicity and p_T spectra of J/ψ has been constructed. The calculation of systematic uncertainty in different multiplicity bins is shown in the appendix section. 8.19. Fig.4.22 shows the p_T spectra of J/ψ for the integrated multiplicity.

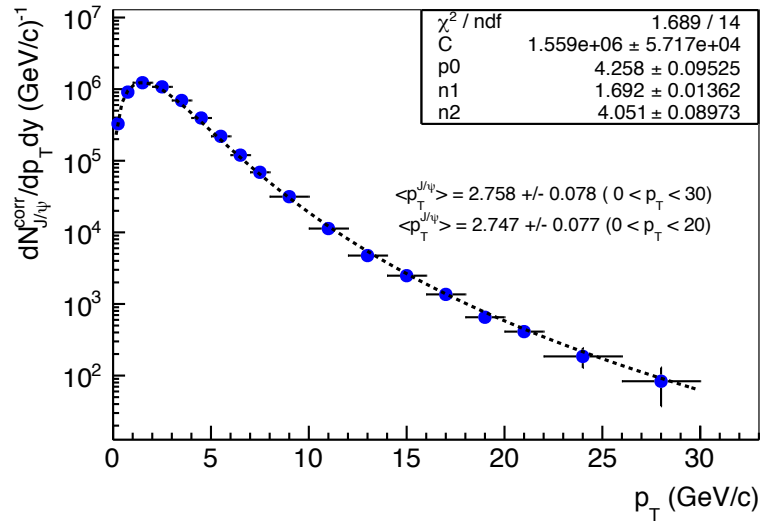


Figure 4.22. p_T spectra of J/ψ for the integrated multiplicity [116].

To extract the $\langle p_T \rangle$ of J/ψ , Eq. 4.31 has been used to fit the p_T spectra. The quality of the fit can be seen from the figure.4.22. Then, we have used the formula given in Eq.4.32 to calculate the $\langle p_T \rangle$ of J/ψ .

$$f(p_T) = C \times \frac{p_T}{(1 + (\frac{p_T}{p_0})^{n_1})^{n_2}} \quad (4.31)$$

$$\langle p_T \rangle = \frac{\int p_T f(p_T)}{\int f(p_T)} \quad (4.32)$$

It can be seen that the $\langle p_T \rangle$ of J/ψ obtained from this traditional method is well consistent with the measurement done in the past [148]. Therefore, the discrepancy with the extracted $\langle p_T \rangle$ of J/ψ (section 4.4.2) is because of the fact that dependence of $\langle p_T \rangle$ of J/ψ with mass. The mass variation of $\langle p_T \rangle$ is properly taken care of different kinds of signal functions which is discussed in section. 4.4.4. Please note that this is just only a test to our present method in the current data set which has already been tested with a dedicated analysis [122]. The same test can not be performed in the multiplicity bins due to the lack of statistics.

4.4.4 Variation of dimuon $\langle p_T \rangle$ as a function of invariant mass

During the fitting procedure, the J/ψ $\langle p_T \rangle$ has been considered as a constant free parameter. In order to study the validity of this assumption, the reconstructed di-muon $\langle p_T \rangle$ invariant mass spectrum has been studied in the pure J/ψ simulation used for the $A \times \epsilon$ computation. The invariant mass resolution depends on the precision in the measurement of the angle between the muon pair and their momenta. There are several effects like the event vertex determination, scatterings and energy-loss fluctuations in the muon absorber, and the precision of the tracking chambers which affect the precision of the measurements. Taking this into account all these effects, we may expect a variation of the dimuon $\langle p_T \rangle$ as a function of the invariant mass. Similar kind of variation has been observed and is shown in Fig. 4.20. The result of the reconstructed $\langle p_T \rangle$ as a function of invariant mass is shown in Fig. 4.23 for MC simulations. It can be seen from the figure that the reconstructed J/ψ $\langle p_T \rangle$ is not constant. To parametriz this variation a “piecewise function” (Ref. [114]) has been used to fit $\langle p_T \rangle^{\mu^+ \mu^-}$.

The function is given by $h(m_{\mu^+\mu^-}) = a_0 + \sum_{n=1}^5 a_n(m_{\mu^+\mu^-} - m_{J/\psi})$.

$$\langle p_T \rangle(m_{\mu^+\mu^-}) = \begin{cases} h(2.9) + a_6 \cdot (m_{\mu^+\mu^-} - 2.9) & m_{\mu^+\mu^-} \leq 2.9 \text{ GeV}/c^2 \\ h(m_{\mu^+\mu^-}) & 2.9 \text{ GeV}/c^2 < m_{\mu^+\mu^-} < 3.4 \text{ GeV}/c^2 \\ h(3.4) + a_7 \cdot (m_{\mu^+\mu^-} - 3.4) & m_{\mu^+\mu^-} \geq 3.4 \text{ GeV}/c^2 \end{cases}$$

This function is able to reproduce the variation of the di-muon $\langle p_T \rangle$ in the invariant mass range. In order to extract the J/ψ $\langle p_T \rangle$ value, the fitted function is evaluated at $m_{\mu^+\mu^-} = m_{J/\psi}$. So, we obtain $\langle p_T^{J/\psi} \rangle = a_0$. The fit result and the obtained fit parameters are shown in Fig. 4.23. It has been observed that, the obtained $\langle p_T^{J/\psi} \rangle$ is not the same as the input one (input $\langle p_T^{J/\psi} \rangle = 2.751$). To understand the difference in $\langle p_T \rangle$ of J/ψ , we have also performed the cross-check with 2015 data set and the result can be seen from the section. 8.18 in the appendix. In case of 2015 data set the second peak around the signal has not been observed. Therefore, we suppose that the second peak around the signal is arising because of the detector/measurement constraints in 2016 data sample and hence in the difference of $\langle p_T \rangle$ of MC input and the obtained value.

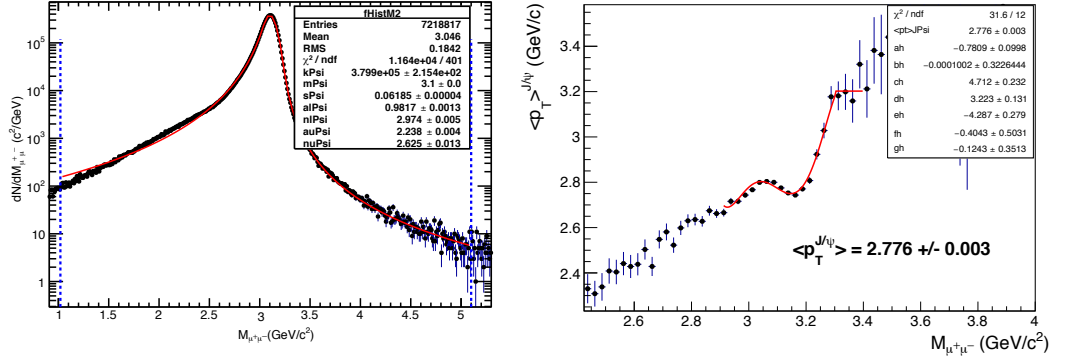


Figure 4.23. Fit to the multiplicity integrated, $A \times \epsilon$ corrected, reconstructed di-muon invariant mass spectrum in MC (left) and the corresponding $\langle p_T \rangle$ (right) where the $A \times \epsilon$ map used is calculated from same the MC [116].

To take into account the variation of di-muon $\langle p_T \rangle$ as a function of the invariant mass in the data (the second peak around the signal), we have tested

with the parametrization of $\langle p_T^{J/\psi} \rangle$ as “piece wise function”, “Pol4(x-3.096)” and “Flat+Lilear” function. We have mentioned the functional form of “piece-wise” function in the above paragraph. Following are the functional form of other two functions:

Pol4(x-3.096):

$$\begin{aligned} \langle p_T^{J/\psi} \rangle(m_{\mu^+\mu^-}) = & \langle p_T^{J/\psi} \rangle + [a_1(m_{\mu^+\mu^-} - 3.096916)] \\ & + [a_2(m_{\mu^+\mu^-} - 3.096916)]^2 + [a_3(m_{\mu^+\mu^-} - 3.096916)]^3 \\ & + [a_4(m_{\mu^+\mu^-} - 3.096916)]^4 \end{aligned}$$

Flat+Linear:

$$\langle p_T \rangle(m_{\mu^+\mu^-}) = \begin{cases} \langle p_T^{J/\psi} \rangle & m_{\mu^+\mu^-} \leq 3.194 \text{ GeV}/c^2 \\ \langle p_T^{J/\psi} \rangle + a_1(m_{\mu^+\mu^-} - 3.194) & m_{\mu^+\mu^-} > 3.194 \text{ GeV}/c^2 \end{cases}$$

This means $\langle p_T \rangle$ is constant when $m_{\mu^+\mu^-} \leq 3.194 \text{ GeV}/c^2$ and varies linearly when $m_{\mu^+\mu^-} > 3.194 \text{ GeV}/c^2$.

We have used all the discussed parametrizations and fitted the $\langle p_T \rangle^{\mu^+\mu^-}$ as a function of invariant mass to obtain the $\langle p_T^{J/\psi} \rangle$ which properly takes care of the mass variation of $\langle p_T^{J/\psi} \rangle$.

Figure 4.24 shows the variation of $\langle p_T^{J/\psi} \rangle$ with mass. The “piece-wise function” and “Pol4(x-3.096)” functions seem to reproduce the pattern of the peak very well. In the case of “Flat+Linear” function, it is not as good as other two functions to describe both the peaks around the signal. The $\langle p_T^{J/\psi} \rangle$ values obtained from “piece-wise function” and “Pol4(x-3.096)” function perfectly match with that of published result of ALICE, $\langle p_T^{J/\psi} \rangle = 2.745 \pm 0.005 \pm 0.024$ [148]. Whereas, the $\langle p_T^{J/\psi} \rangle$ value obtained using “Flat+Linear” function is same as the value obtained when we consider $\langle p_T^{J/\psi} \rangle$ as a constant parameter. This may be due the fact that the function fails to well describe both the peak.

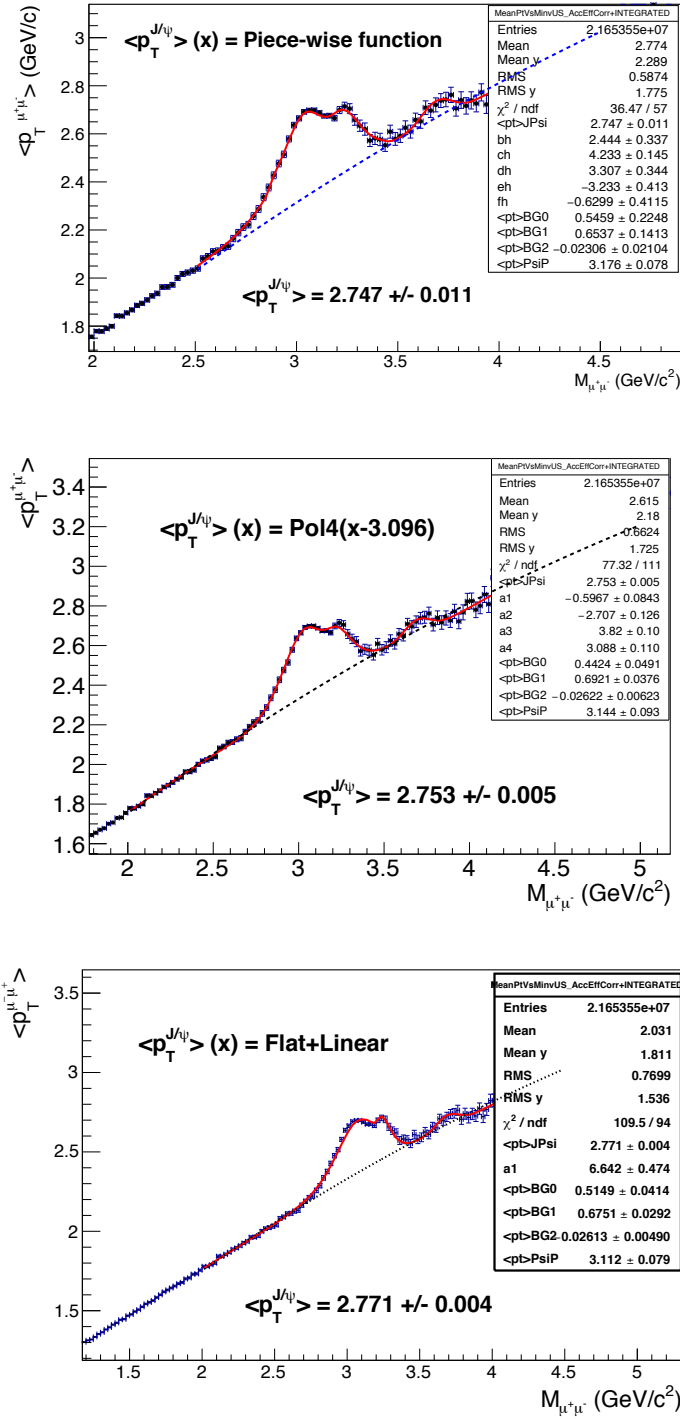


Figure 4.24. Fit to the multiplicity integrated, $A \times \epsilon$ corrected reconstructed di-muon invariant mass spectrum in data with the different functional parametrization of $\langle p_T \rangle$. For all the three cases, Pol2 function is taken as the background function [116].

For the current analysis, we have taken the average of the three methods: $\langle p_T^{J/\psi} \rangle$ as constant parameter, $\langle p_T^{J/\psi} \rangle$ is parametrized as “piece-wise function” and $\langle p_T^{J/\psi} \rangle$ as “Pol4(x-3.096)” to calculate the $\langle p_T^{J/\psi} \rangle$. From the quality of fitting point of view “piece-wise function” is the best function to parametrize $\langle p_T^{J/\psi} \rangle$. However, a continuous function has been tested to account the variation of $\langle p_T^{J/\psi} \rangle$ with mass, hence “Pol4(x-3.096)” is a good assumption. As discussed, the $\langle p_T^{J/\psi} \rangle$ is not constant with mass. Since this variation is approximately the same in the integrated and bin-by-bin extraction, therefore it is worth testing the variation in the multiplicity bin as well, although the second peak around the signal is not prominent due to the statistical fluctuation. We have tested the variation in the multiplicity bins by parametrizing the $\langle p_T^{J/\psi} \rangle$ with “Pol4(x-3.096)” and “Flat+Linear” functions. One can see the fitting results in the appendix section. 8.21. For a comparative study, we have tabulated the values of $\langle p_T^{J/\psi} \rangle$ obtained in each multiplicity bins by taking “Pol4(x-3.096)” and “Flat+Linear” function parametrized to $\langle p_T^{J/\psi} \rangle$. From the table 4.5, it can be clearly seen that the $\langle p_T^{J/\psi} \rangle$ value obtained in both the fit assumptions match with the $\langle p_T^{J/\psi} \rangle$ when it is considered as a constant parameter. This may be due to the large statistical fluctuation in multiplicity bins and that’s why the mass dependence of $\langle p_T \rangle$ is not prominent.

$\langle p_T \rangle$ of J/ψ in different multiplicity bins using different mass variation			
Mult. class	J/ψ - $\langle p_T \rangle$ (Constant) (GeV/c)	J/ψ - $\langle p_T \rangle$ (Flat+Linear) (GeV/c)	J/ψ - $\langle p_T \rangle$ (Pol4(x-3.096)) (GeV/c)
Integrated	2.767 ± 0.004 (0.14 %) ± 0.003 (0.098%)	2.773 ± 0.004	2.753 ± 0.005
1.0 - 8.0	2.347 ± 0.009 (0.39 %) ± 0.003 (0.13%)	2.346 ± 0.009	2.335 ± 0.011
9.0 - 14.0	2.626 ± 0.009 (0.35%) ± 0.003 (0.11%)	2.629 ± 0.009	2.608 ± 0.011
15.0 - 20.0	2.774 ± 0.009 (0.34%) ± 0.006 (0.21%)	2.777 ± 0.01	2.758 ± 0.012
21.0 - 25.0	2.875 ± 0.012 (0.42%) ± 0.002 (0.06%)	2.872 ± 0.012	2.873 ± 0.015
26.0 - 33.0	2.916 ± 0.011 (0.39%) ± 0.003 (0.11%)	2.924 ± 0.011	2.899 ± 0.014
34.0 - 41.0	3.004 ± 0.015 (0.51%) ± 0.005 (0.15%)	3.006 ± 0.015	2.977 ± 0.019
42.0 - 50.0	3.011 ± 0.02 (0.66%) ± 0.0102 (0.34%)	3.012 ± 0.02	2.985 ± 0.025
51.0 - 60.0	3.096 ± 0.023 (0.96%) ± 0.0105 (0.34%)	3.105 ± 0.031	3.084 ± 0.038
61.0 - 80.0	3.182 ± 0.043 (1.35%) ± 0.0211 (0.66%)	3.205 ± 0.045	3.179 ± 0.059
80.0 - 115.0	3.320 ± 0.136 (4.09%) ± 0.162 (4.88%)	3.198 ± 0.139	3.333 ± 0.170

Table 4.5. $\langle p_T \rangle$ of J/ψ in different multiplicity bins using different parametrization for mass variation.

4.4.5 Systematic uncertainty on $\langle p_T^{J/\psi} \rangle$

In the following sub sections, each effect to the measurement of $\langle p_T \rangle$ of J/ψ is studied in detail. The $\langle p_T \rangle$ fitting extraction procedure uncertainties are first studied similarly to those for the signal extraction. The uncertainties on input shape for $A \times \epsilon$ MC are also studied. Other uncertainties like, tracking efficiency uncertainty, the uncertainty on the trigger efficiency, the uncertainty on the matching efficiency between the tracking and the trigger will be considered as a global uncertainty to the measurement of $\langle p_T \rangle$ of J/ψ . Lastly, we have also calculated the uncertainty related to variation of invariant mass with signal.

Systematic uncertainty on $\langle p_T^{J/\psi} \rangle$ extraction

Following are the different sources of systematic uncertainties taken into account for the extraction of $\langle p_T \rangle$ of J/ψ .

- M_{inv} signal function
- M_{inv} background function
- M_{inv} tail parameter
- $f(\langle p_T \rangle)$ background function
- fitting range

An example of the results for different set of tests is shown in Fig. 4.25 for the integrated multiplicity and integrated p_T . We have opted the same procedure to extract $\langle p_T \rangle$ of J/ψ in different multiplicity bin and the results can be seen from appendix section 8.22. The value of $\langle p_T \rangle$ of J/ψ along with their statistical and systematic uncertainty are tabulated in table 4.6. The systematic uncertainties of relative $\langle p_T \rangle$ of J/ψ have been calculated by varying the background functions of signal and $\langle p_T \rangle$, tail parameter, fitting range of multiplicity bin corresponding to each signal function. Example plots showing relative $\langle p_T \rangle$ of

J/ψ for low and high multiplicity bin are shown in the Fig. 4.26 and Fig. 4.27. The results of relative $\langle p_T \rangle$ of J/ψ for all other multiplicity bin can be found from appendix section. 8.23. Absolute $\langle p_T \rangle$ and relative $\langle p_T \rangle$ of J/ψ for the analysed charged-particle bin are shown in table. 4.6.

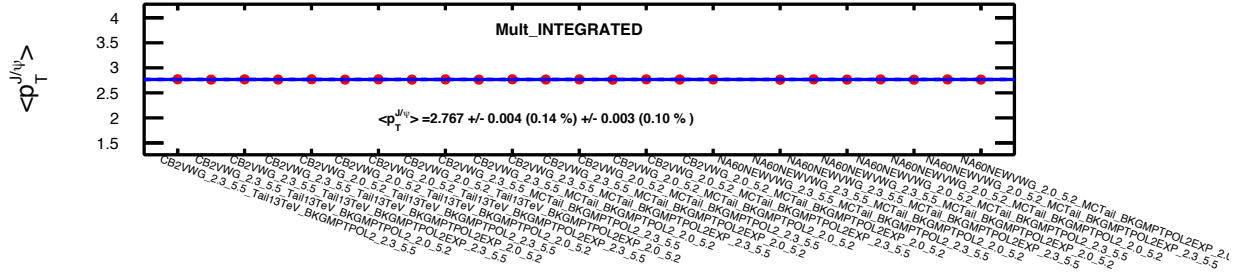


Figure 4.25. Extraction of $\langle p_T \rangle$ of J/ψ taking different combination of tests for integrated multiplicity and integrated p_T [116].

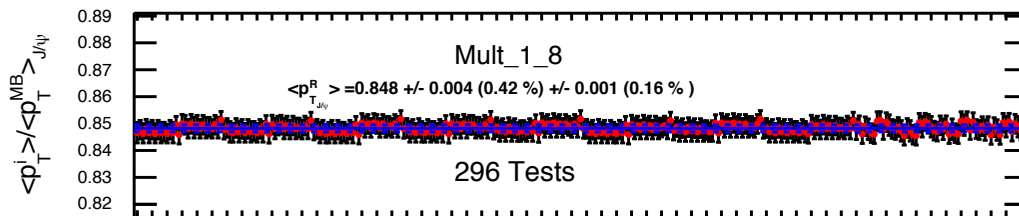


Figure 4.26. Relative $\langle p_T \rangle$ of J/ψ taking different combination of tests for the multiplicity bin [1-8] in the integrated p_T [116].

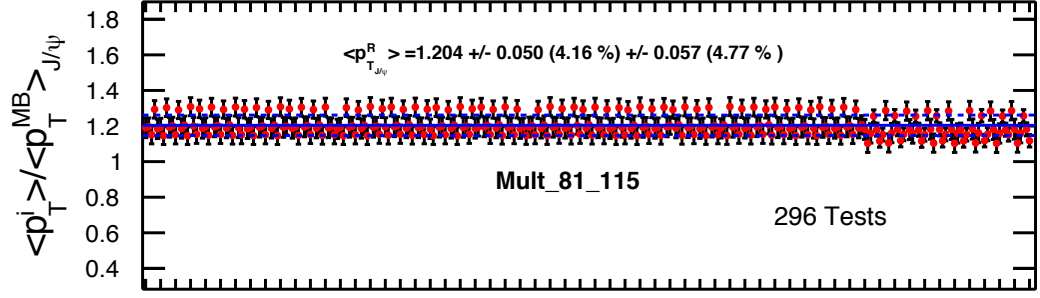


Figure 4.27. Relative $\langle p_T \rangle$ of J/ψ taking different combination of tests for the multiplicity bin [81-115] in the integrated p_T [116].

$\langle p_T \rangle$ and $\langle p_T \rangle^R$ of J/ψ in different multiplicity bins		
Multiplicity Class	$J/\psi\text{-}\langle p_T \rangle$ (GeV/c)	Relative $J/\psi\text{-}\langle p_T \rangle$
Integrated	$2.767 \pm 0.004 (0.14\%) \pm 0.003 (0.098\%)$	—
1.0 - 8.0	$2.347 \pm 0.009(0.39\%) \pm 0.003(0.13\%)$	$0.848 \pm 0.003(0.417\%) \pm 0.001(0.16\%)$
9.0 - 14.0	$2.626 \pm 0.009(0.35\%) \pm 0.003 (0.11\%)$	$0.949 \pm 0.004(0.38\%) \pm 0.001(0.16\%)$
15.0 - 20.0	$2.774 \pm 0.009(0.34\%) \pm 0.006 (0.21\%)$	$1.002 \pm 0.004(0.38\%) \pm 0.002(0.22\%)$
21.0 - 25.0	$2.875 \pm 0.012(0.42\%) \pm 0.002(0.06\%)$	$1.039 \pm 0.005(0.45\%) \pm 0.001(0.11\%)$
26.0 - 33.0	$2.916 \pm 0.011(0.39\%) \pm 0.003(0.11\%)$	$1.054 \pm 0.004(0.41\%) \pm 0.002(0.15\%)$
34.0 - 41.0	$3.004 \pm 0.015(0.51\%) \pm 0.005(0.15\%)$	$1.086 \pm 0.006(0.53\%) \pm 0.002(0.18\%)$
42.0 - 50.0	$3.011 \pm 0.02 (0.66\%) \pm 0.0102(0.34\%)$	$1.088 \pm 0.007(0.68\%) \pm 0.004(0.37\%)$
51.0 - 60.0	$3.096 \pm 0.023(0.96\%) \pm 0.0105(0.34\%)$	$1.120 \pm 0.011(0.99\%) \pm 0.003(0.28\%)$
61.0 - 80.0	$3.182 \pm 0.043(1.35\%) \pm 0.0211(0.66\%)$	$1.151 \pm 0.016(1.39\%) \pm 0.006(0.54\%)$
80.0 - 115.0	$3.320 \pm 0.136(4.09\%) \pm 0.162(4.88\%)$	$1.204 \pm 0.050(4.16\%) \pm 0.057(4.77\%)$

Table 4.6. $\langle p_T \rangle$ and relative $\langle p_T \rangle$ of J/ψ in different multiplicity bins.

4.4.6 Systematic uncertainty from variation of $\langle p_T \rangle^{J/\psi}$ with invariant mass

As discussed in section. 4.4.4, we have taken the average of the three method: $\langle p_T^{J/\psi} \rangle$ as constant parameter, $\langle p_T^{J/\psi} \rangle$ is parametrized as “piece-wise function” and $\langle p_T^{J/\psi} \rangle$ as “Pol4(x-3.096)” to calculate the $\langle p_T^{J/\psi} \rangle$ for integrated multiplicity.

For the completeness, we have tabulated the functional parametrization and the obtained $\langle p_T \rangle^{J/\psi}$ in table. 4.7.

$\langle p_T^{J/\psi} \rangle$ taking into account its variation with mass in data	
Function used to parametrized $\langle p_T \rangle^{J/\psi}$	$\langle p_T \rangle^{J/\psi}$
$\langle p_T \rangle$ as constant parameter	2.767 ± 0.004
$\langle p_T \rangle =$ “piece-wise” function	2.747 ± 0.011
$\langle p_T \rangle = \text{Pol4}(x-3.096)$	2.753 ± 0.006

Table 4.7. $\langle p_T \rangle$ of J/ψ taking into account the variation of $\langle p_T \rangle$ with mass.

The mean value and corresponding statistical as well as systematic uncertainty are calculated using the following formulas,

$$\langle X \rangle = \frac{1}{n_{tests}} \sum_{i=1}^{n_{tests}} X_i \quad (4.33)$$

$$\sigma_{\langle X \rangle}^{syst} = \sqrt{\frac{\sum_{i=1}^{n_{tests}} (X_i - \langle X \rangle)^2}{n_{tests}}} \quad (4.34)$$

$$\sigma_{\langle X \rangle}^{stat} = \frac{1}{n_{tests}} \sum_{i=1}^{n_{tests}} \sigma_{X_i} \quad (4.35)$$

Where, X_i is the quantity obtained in each test, $\langle X \rangle$ is the mean of X_i and σ_{X_i} is the statistical error in each test. Using the mentioned formula, we obtained value of $\langle p_T \rangle^{J/\psi} = \mathbf{2.756 \pm 0.007 (0.25\%) \pm 0.008 (0.3\%)}$, for the integrated multiplicity. Besides, these sources of systematic uncertainty one can not ignore the difference in the input $\langle p_T \rangle$ of J/ψ and the $\langle p_T \rangle^{J/\psi}$ obtained from the fitting of MC. The difference between the two must be assign as a another source of systematic uncertainty to the calculation of $\langle p_T \rangle$ of J/ψ . In the table. 4.8, we have enlisted the values and detailed about it is discussed in section. 4.4.4.

$\langle p_T^{J/\psi} \rangle$ from MC	
Input $\langle p_T \rangle$ in MC	2.752
$\langle p_T \rangle$ value obtained from MC fit	2.776

Table 4.8. $\langle p_T \rangle$ obtained from MC

The difference between the input and obtained $\langle p_T \rangle$ of J/ψ in MC is 0.024, which is added in quadrature to the existing systematic uncertainty of $\langle p_T \rangle^{J/\psi}$. Therefore, $\langle p_T \rangle^{J/\psi} = 2.756 \pm 0.007$ (0.25%) ± 0.025 (0.91%) for the integrated multiplicity. Different sources of systematic uncertainty contributing to the multiplicity integrated $\langle p_T^{J/\psi} \rangle$ are listed in table. 4.9.

Sources of systematic uncertainty to the integrated $\langle p_T^{J/\psi} \rangle$	
Sources $\langle p_T \rangle^{J/\psi}$	Syst. Uncertainty
From the signal extraction	0.1 %
Variation $\langle p_T \rangle^{J/\psi}$ with mass obtained from data	0.3%
Mismatch of $\langle p_T \rangle^{J/\psi}$ obtained from MC	0.9%

Table 4.9. Sources of systematic uncertainty contributing to the multiplicity integrated $\langle p_T^{J/\psi} \rangle$

As discussed in the previous section, since this variation is approximately the same in the integrated and bin-by-bin extraction, we can consider that this effect vanish on the relative J/ψ $\langle p_T \rangle$. For the absolute J/ψ $\langle p_T \rangle$, we consider the same systematic effect in multiplicity bin as that of integrated case (2.4%) in order to be conservative.

4.4.7 Systematic uncertainty on MC input

The uncertainty on the MC input shapes is evaluated by the following steps:

- Data sample is divided into three parts: Low ($N_{Trk}^{corr} < 40$), High ($N_{Trk}^{corr} > 40$) and Integrated multiplicity

- p_T and y -spectra have been evaluated for the three cases, and we have fitted the p_T and y -spectra using the following functions,

$$f(p_T) = C \times \frac{p_T}{(1 + (\frac{p_T}{p_0})^{n_1})^{n_2}} \quad f(y) = C \times e^{-\frac{1}{2} \times [(y-\mu)/\sigma]^2}$$

- The relative $f(p_T)$ [$Ref(p_T)$] and relative $f(y)$ [$Ref(y)$] for low and high multiplicity is evaluated (by taking ratio w.r.t $f(p_T)$ and $f(y)$ of integrated multiplicity)

- Then the following weight factors are evaluated,

$$- w_1 = Ref(p_T)_{Low} \times Ref(y)_{Low}, \text{ where } w_1 \text{ is a function of } p_T \text{ and } y.$$

$$- w_2 = Ref(p_T)_{Low} \times Ref(y)_{High}, \text{ where } w_2 \text{ is a function of } p_T \text{ and } y.$$

$$- w_3 = Ref(p_T)_{High} \times Ref(y)_{Low}, \text{ where } w_3 \text{ is a function of } p_T \text{ and } y.$$

$$- w_4 = Ref(p_T)_{High} \times Ref(y)_{High}, \text{ where } w_4 \text{ is a function of } p_T \text{ and } y.$$

- These weight factors are used to reweight default (integrated multiplicity) $A \times \epsilon$ map to produce four different maps for the evaluation of systematic uncertainty.

Figure. 4.28 shows each step to calculate the weight factors. First, we have fitted the p_T and y -spectra and then the relative p_T ($(p_T)_{Low}/(p_T)_{Default}$, $(p_T)_{High}/(p_T)_{Default}$) and relative y ($y_{Low}/y_{Default}$, $y_{High}/y_{Default}$) spectra have been calculated. Finally, in the last two figures of Fig. 4.28, we have shown the combined function for $Ref(p_T)_{Low} \times Ref(y)_{Low}$.

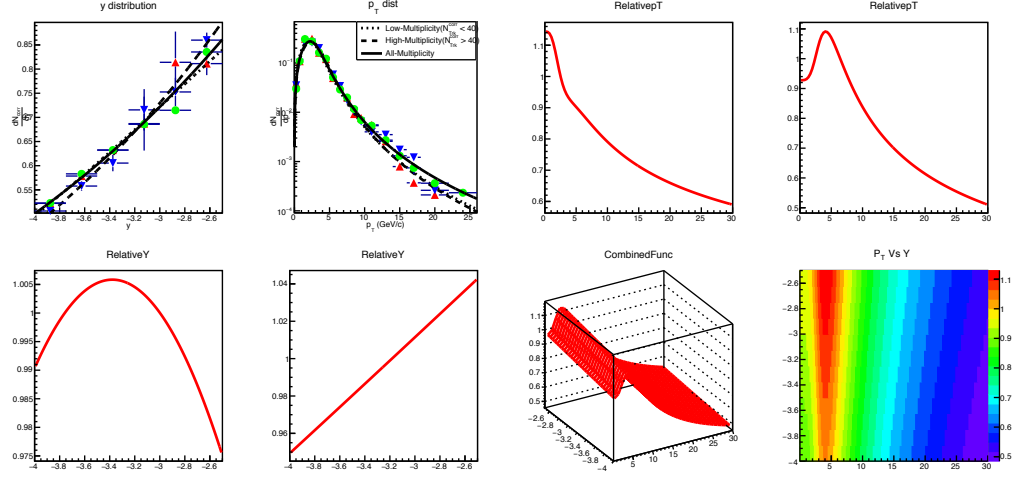


Figure 4.28. Steps to extract the weighted AccXEff maps. The last two figures are combined function for $Ref(p_T)_{Low} \times Ref(y)_{Low}$ combination [116].

Using all the four $A \times \epsilon$ maps (Appendix.), we have evaluated the $\langle p_T \rangle$ of J/ψ and calculated their deviation from the default value (integrated multiplicity). The relative difference of the $\langle p_T^{J/\psi} \rangle$ is obtained from different combinations w.r.t default one as follow,

$$\Delta R_{\langle p_T^{J/\psi} \rangle} = \frac{|\langle p_T^{J/\psi} \rangle_{Default} - \langle p_T^{J/\psi} \rangle|}{\langle p_T^{J/\psi} \rangle_{Default}} \quad (4.36)$$

We have neglected the statistical uncertainty (and are correlated between two distributions), which leads to increase in uncertainty of the quantity $\Delta R_{J/\psi}$. The uncertainty is taken as Gaussian and is calculated as,

$$\sigma_{MC \text{ input}} = \Delta R_{\langle p_T^{J/\psi} \rangle} / \sqrt{12} \quad (4.37)$$

The relative deviation of all the combinations (Low-Low, Low-High, High-Low and High-High) w.r.t default value is calculated for all the multiplicity bins and is shown in Fig. 4.29. A maximum deviation of around 3% is observed in the last multiplicity bin and in all other bins the deviation is nearly zero.

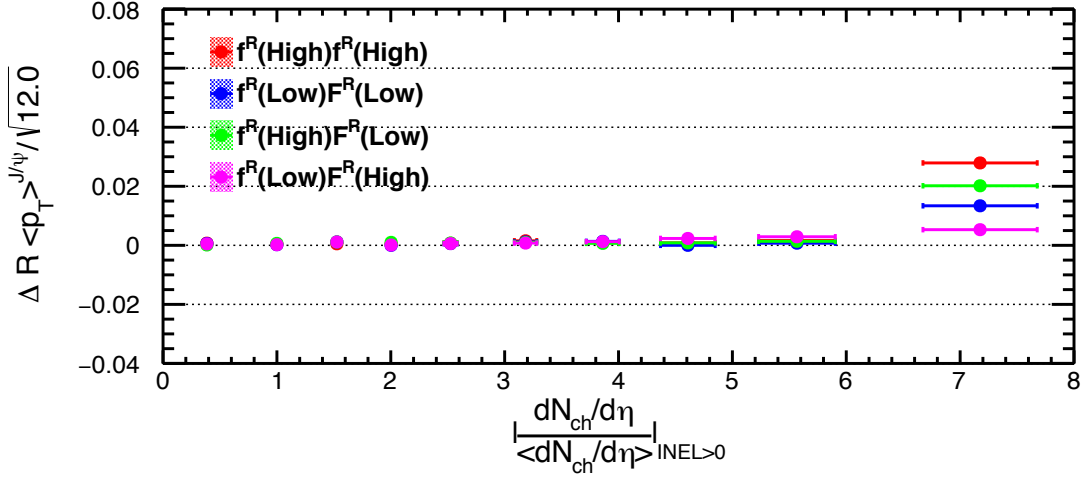


Figure 4.29. The relative deviation of $\langle p_T^{J/\psi} \rangle$ for all the combinations (Low-Low, Low-High, High-Low and High-High) w.r.t the default value [116].

4.4.8 Handling of global uncertainties

Following are the points which has been considered for handling of the uncertainties of $\langle p_T^{J/\psi} \rangle$ and relative $\langle p_T^{J/\psi} \rangle$:

- **Systematic uncertainty from the signal extraction:** It should be evaluated directly on the mean p_T ratio, using the many fits, e.g Fig. 4.27. There will be no “global” uncertainty on the signal extraction for the $\langle p_T \rangle$ ratio (relative $\langle p_T \rangle$), because it is by construction cancel out.
- **Statistical uncertainties:** The statistical uncertainty on integrated $\langle p_T \rangle$ is considered as “global uncertainty” and using the following standard error propagation formula, we have evaluated the statistical uncertainty on relative $\langle p_T^{J/\psi} \rangle$:

The formula for standard division error propagation is,

$$Err(x/y) = (x/y) * \sqrt{[(\delta x/x)^2 + (\delta y/y)^2]} \quad (4.38)$$

Here, $x = \langle p_T^i \rangle$ and $\delta x =$ Statistical uncertainty in $\langle p_T^i \rangle$, where “i” stands for i^{th} multiplicity bin.

$y =$ integrated $\langle p_T \rangle$ and $\delta y =$ Statistical uncertainty in integrated $\langle p_T \rangle = 0$ (as it is taken as *global* uncertainty).

- **Central value of relative $\langle p_T^{J/\psi} \rangle$:** The ratio of $\langle p_T^{J/\psi} \rangle$ in i^{th} multiplicity bin to that of integrated multiplicity has been taken as central value. To be noted here that these values are very close to that of the value obtained from the tests average (e.g Fig. 4.27). The calculated values up to the present step is given in the table. 4.10.

$\langle p_T \rangle$ and $\langle p_T \rangle^R$ of J/ψ (Step1)		
Multiplicity Class	$J/\psi - \langle p_T \rangle$ (GeV/c)	Relative $J/\psi - \langle p_T \rangle$
Integrated	2.756 ± 0.007 (0.25 %) ± 0.003 (0.098%)	—
1.0 - 8.0	2.347 ± 0.009 (0.39 %) ± 0.003 (0.13%)	0.852 ± 0.003 (0.38 %) ± 0.001 (0.16%)
9.0 - 14.0	2.626 ± 0.009 (0.35%) ± 0.003 (0.11%)	0.953 ± 0.003 (0.34%) ± 0.001 (0.10%)
15.0 - 20.0	2.774 ± 0.009 (0.34%) ± 0.006 (0.21%)	1.006 ± 0.003 (0.32%) ± 0.002 (0.19%)
21.0 - 25.0	2.875 ± 0.012 (0.42%) ± 0.002 (0.06%)	1.043 ± 0.004 (0.42%) ± 0.001 (0.09%)
26.0 - 33.0	2.916 ± 0.011 (0.39%) ± 0.003 (0.11%)	1.059 ± 0.004 (0.38%) ± 0.002 (0.19%)
34.0 - 41.0	3.004 ± 0.015 (0.51%) ± 0.005 (0.15%)	1.090 ± 0.005 (0.5%) ± 0.002 (0.18%)
42.0 - 50.0	3.011 ± 0.02 (0.66%) ± 0.010 (0.34%)	1.092 ± 0.007 (0.66%) ± 0.004 (0.37%)
51.0 - 60.0	3.096 ± 0.023 (0.96%) ± 0.010 (0.34%)	1.123 ± 0.008 (0.74%) ± 0.003 (0.27%)
61.0 - 80.0	3.182 ± 0.043 (1.35%) ± 0.021 (0.66%)	1.154 ± 0.015 (1.35%) ± 0.006 (0.52%)
80.0 - 115.0	3.320 ± 0.136 (4.09%) ± 0.162 (4.88%)	1.205 ± 0.049 (4.1%) ± 0.057 (4.73%)

Table 4.10. $\langle p_T \rangle$ and $\langle p_T \rangle^R$ of J/ψ

- **Uncertainty from mass variation and MC $\langle p_T \rangle$ mismatch:** The *global* uncertainty on the multiplicity-integrated $\langle p_T \rangle$ is evaluated by adding the uncertainty from mass variation (0.007) and MC $\langle p_T \rangle$ mismatch (0.024) to the statistical uncertainty. Whereas, the systematic uncertainty on the per-multiplicity-bin $\langle p_T \rangle$ is calculated by propagating it to the $\langle p_T \rangle$ ratio and added in quadrature to the point-to-point systematic uncertainty as follows:

$$\begin{aligned}
& \text{Systematic uncertainty in relative } \langle p_T \rangle \text{ of } i^{\text{th}} \text{ bin}(\text{Syst.} \langle p_T^{R,i} \rangle) \\
& \text{Syst.} \langle p_T^{R,i} \rangle = \langle p_T^{R,i} \rangle * \sqrt{[(\delta x)^2 + (\delta y)^2 + (\delta z)^2]} \quad (4.39)
\end{aligned}$$

Where $\delta x = 0.024/2.752 = 0.008$ (relative uncertainty in MC $\langle p_T \rangle$ mismatch)

$\delta y = 0.007/2.756 = 0.0025$ (relative uncertainty in mass variation) and

$\delta z =$ relative uncertainty on $\langle p_T^i \rangle$ (e.g: for the last bin, $0.057/1.205 = 0.0473$)

- MC input systematics on the $A \times \epsilon$ map:** The obtained systematic uncertainty on each multiplicity bin (section. 4.4.7) is added to the point-to-point systematic uncertainty by quadrature. In the current analysis, the systematic uncertainty due to $A \times \epsilon$ map is negligible in all the multiplicity bin as well as integrated multiplicity, except the last bin (where the value is 0.003). If we add 0.003 to the systematic uncertainty of last bin (0.058) quadratically, the value will remain unchanged (0.058). So, in general, the MC input systematics on the $A \times \epsilon$ map to all the multiplicity bins are negligible.
- Uncertainties such as the uncertainty on the trigger, tracking, and trigger-track matching efficiencies need to be considered in the *global* systematic uncertainty.

$\langle p_T \rangle^R$ of J/ψ (Step2)	
Integrated $\langle p_T \rangle$	2.756 ± 0.007 (0.25 %) ± 0.025 (0.91%) (GeV/c)
Mult. class	Relative J/ψ - $\langle p_T \rangle$
1.0 - 8.0	0.852 ± 0.003 (0.38 %) ± 0.008 (0.94%)
9.0 - 14.0	0.953 ± 0.003 (0.34%) ± 0.009 (0.94%)
15.0 - 20.0	1.006 ± 0.003 (0.32%) ± 0.009 (0.9%)
21.0 - 25.0	1.043 ± 0.004 (0.42%) ± 0.01 (0.96%)
26.0 - 33.0	1.059 ± 0.004 (0.38%) ± 0.01 (0.94%)
34.0 - 41.0	1.090 ± 0.005 (0.5%) ± 0.01 (0.92%)
42.0 - 50.0	1.092 ± 0.007 (0.66%) ± 0.011 (1.007%)
51.0 - 60.0	1.123 ± 0.008 (0.74%) ± 0.011 (0.98%)
61.0 - 80.0	1.154 ± 0.015 (1.35%) ± 0.012 (1.039%)
80.0 - 115.0	1.205 ± 0.049 (4.1%) ± 0.058 (4.813%)

Table 4.11. Relative $\langle p_T \rangle$ of J/ψ after considering global uncertainty.

4.5 Results and discussions

In this section, we have discussed the results obtained from the ALICE data analyses. The results of the J/ψ relative yield and relative $\langle p_T \rangle$ as a function of relative charged-particle multiplicity has been approved by ALICE as “ALICE Preliminary” which are presented at Hard-Probes-2018 [129, 130] and Strangeness in Quark Matter-2019 [131]. These results will be part of an ALICE publication which is under preparation [116] after the approval of Physics Board. Please note that the updated results do not change the physics out put of the analysis.

4.5.1 Relative yield of J/ψ as a function of multiplicity

Using the previously discussed ingredients, we computed the relative yield of J/ψ as a function of the relative charged-particle pseudorapidity density at forward rapidity ($2.5 < y < 4.0$). In the Fig. 4.30, the relative J/ψ yield measured in so called *INEL* > 0 collisions defined as, inelastic collisions having at least one charged-particle within $|\eta| < 1.0$ is shown.

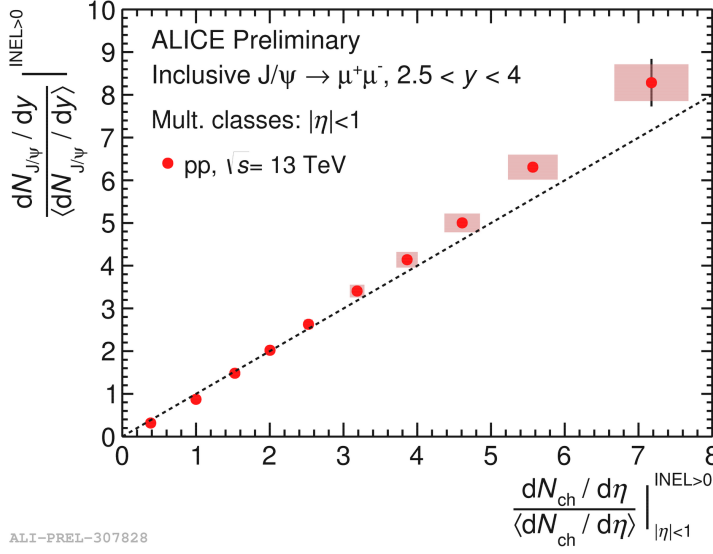


Figure 4.30. Forward-rapidity self-normalised J/ψ yields as a function of self-normalised charged particle multiplicity measured at mid-rapidity ($|\eta| < 1.0$) in pp collisions at $\sqrt{s} = 13$ TeV [116, 129, 130]. The dashed line represents the diagonal line, $y = x$.

We observe a linear increase of relative J/ψ yield as a function of multiplicity and the behavior is similar to that observed in pp collisions at $\sqrt{s} = 7$ TeV [65]. With the higher multiplicity reach in pp collisions at $\sqrt{s} = 13$ TeV, the same linear scaling of relative yield of J/ψ with relative multiplicity further reveals the importance of Multipartonic interaction (MPI) in the production of J/ψ . In the MPI scenario, the charged-particle multiplicity is a proxy to the number of partonic interactions in a pp event. If MPI extend up to a regime of hard processes, the yield of J/ψ should also scale with the number of partonic interactions and the observed correlation will result. The dotted line in the figure represents a linear line ($y = x$), to show the linear deviation of the behavior. Another interpretation of the observed correlation is that the hadronic event activity affects the same way to the production of charged-particle and J/ψ . To have a quantitative idea of linear scaling of J/ψ with charged-particle multiplicity and in particular MPI, we have calculated the ratio of relative yield of J/ψ to relative charged-particle density and plotted it as a function of charged-particle multiplicity.

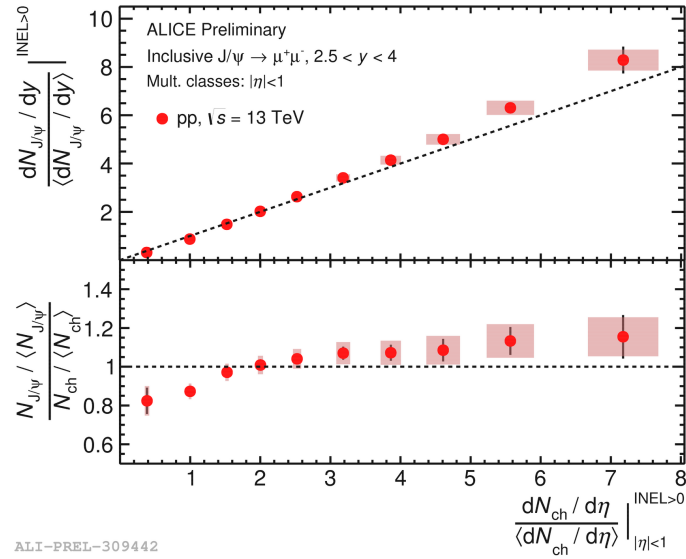


Figure 4.31. Forward-rapidity self-normalised J/ψ yields as a function of self-normalised charged particle multiplicity measured at mid-rapidity ($|\eta| < 1.0$) in pp collisions at $\sqrt{s} = 13$ TeV [116, 129, 130]. The bottom panel represents the ratio of relative yield of J/ψ to relative charged-particle density. The dashed line represents the diagonal line, $y = x$.

It can be seen from Fig. 4.31 that the points are crossing the line along unity around $dN_{\text{ch}}^R/d\eta \approx 1.6$. It shows that the MPI scaling to the production of J/ψ is not perfectly linear. Further, the center-of-mass energy dependence of the relative yield of J/ψ with multiplicity has been studied by comparing the result of $\sqrt{s} = 13$ TeV with that of $\sqrt{s} = 5.02$ TeV at forward rapidity in pp collisions. The comparison plot is shown in Fig. 4.32. We have observed a similar trend at $\sqrt{s} = 5.02$ TeV and 13 TeV, indicating that particle production is dominantly driven by the hadronic event activity independently of $\sqrt{s}$.

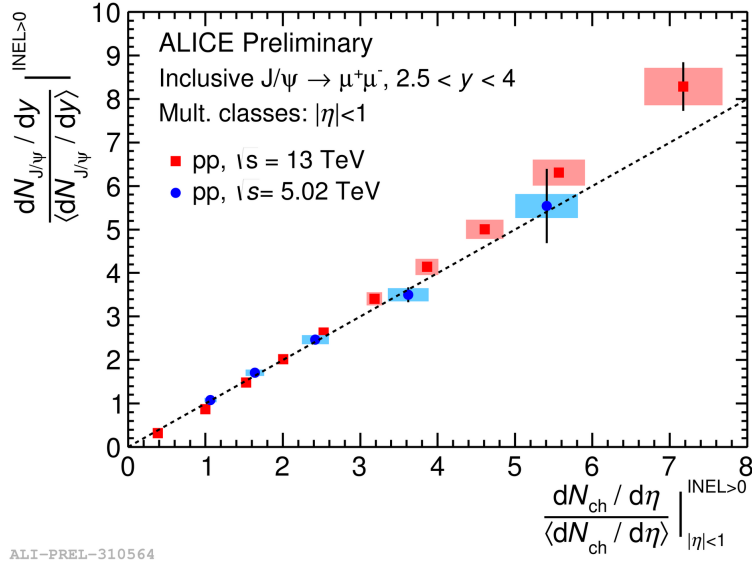


Figure 4.32. Forward-rapidity self-normalised J/ψ yields as a function of self-normalised charged particle multiplicity measured at mid-rapidity ($|\eta| < 1.0$) in pp collisions at $\sqrt{s} = 5.02$ and 13 TeV [116, 129, 130]. The dashed line represents the diagonal line, $y = x$.

On the contrary, when we compare the measurements of J/ψ at forward rapidity with the J/ψ measurements at mid-rapidity ($|\eta| < 0.9$), i.e with no rapidity gap between the signal and the charged-particle density estimator ($|\eta| < 1$), a faster than linear increase of J/ψ yield has been observed. The different trends observed with the introduction of a rapidity gap might hint to auto-correlations and/or jet biases.

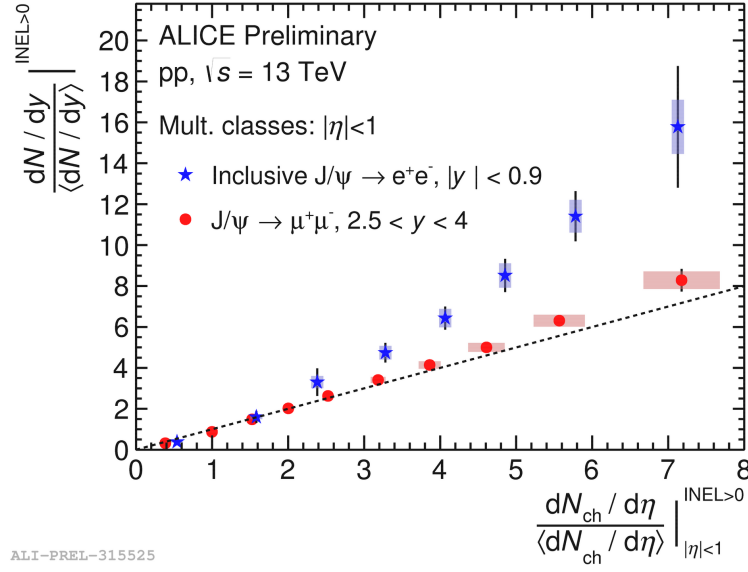


Figure 4.33. Relative J/ψ yield as a function of the relative charged-particle density measured at mid and forward rapidity in pp collisions at $\sqrt{s} = 13$ TeV and at forward rapidity in pp collisions at $\sqrt{s} = 5.02$ TeV. The dotted line corresponds to a linear increase [116, 129, 130].

To investigate the possible dependence of the observed increase on the quark content of the quarkonium state, and on its mass, a similar study of the relative $\Upsilon(1S)$ and $\Upsilon(2S)$ yields as a function of the relative charged-particle density has been performed in pp collisions at $\sqrt{s} = 13$ TeV. We have performed a comparison study of J/ψ with Υ and it is presented in Fig. 4.34. As like J/ψ , a linear increase of the relative $\Upsilon(1S)$ and $\Upsilon(2S)$ yields as a function of multiplicity has been observed. The multiplicity dependence is the same for the various quarkonium states despite of their different masses and binding energies. Moreover, when we compare the multiplicity dependence of quarkonia with the similar measurements in light-flavor sector, we observe the trend is same incase of light-flavor as well [134]. This observation, further emphasizing the event activity associated with the particle production in pp collisions do not recognize final state hadronic species.

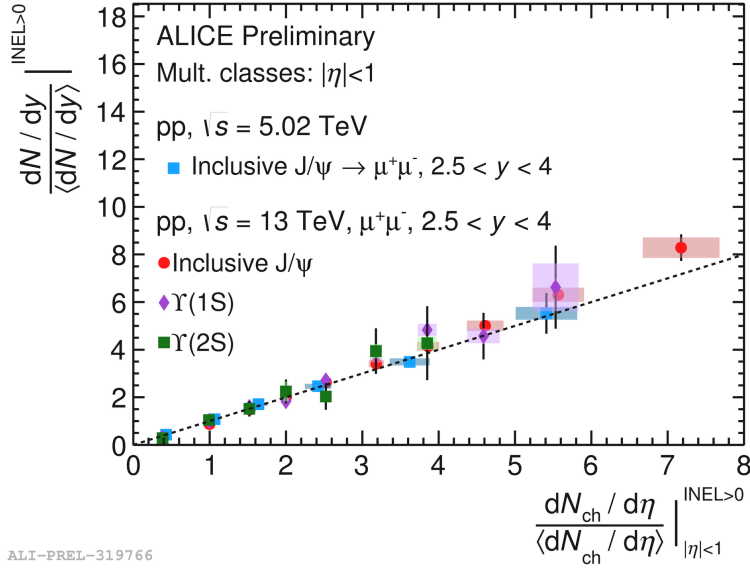


Figure 4.34. Forward-rapidity self-normalised yields of J/ψ and Υ as a function of self-normalised charged-particle multiplicity measured at mid-rapidity ($|\eta| < 1.0$) in pp collisions at $\sqrt{s} = 5.02$ and 13 TeV [116, 129, 130]. The dashed line represents the diagonal line, $y = x$.

4.5.2 $\langle p_T \rangle$ of J/ψ as a function of multiplicity

As we have discussed earlier, to have further insight into the J/ψ production mechanism in pp collisions, we have studied first moment of p_T spectra. Fig. 4.35 shows the average transverse momentum of J/ψ ($\langle p_T \rangle$) versus the relative charged-particle multiplicity as measured in pp collisions at $\sqrt{s} = 13$ TeV. An increase in $\langle p_T \rangle$ with $N_{ch}/\langle N_{ch} \rangle$ with a little saturation towards higher multiplicity is seen. The possible explanation in the MPI perspective is that the high multiplicity events are produced by multiple parton interactions and the incoherent superposition of such interactions would lead to a constant $\langle p_T \rangle$ at high multiplicity [64]. This is the reason of saturation of the $\langle p_T \rangle$ towards the higher multiplicity is seen. Secondly, linear increase of relative J/ψ yield as well as saturation of $\langle p_T \rangle$ with multiplicity could be related to collectivity, as ridge phenomena recently been observed in high-multiplicity pp collisions [69]. Further, when the relative $\langle p_T \rangle$ is studied, the $\langle p_T \rangle$ of J/ψ in multiplicity

bins found to exceed from minimum bias beyond the $N_{ch}/\langle N_{ch} \rangle \approx 1.6$. For the highest multiplicity bin the produced J/ψ have around 1.22 times $\langle p_T \rangle$ w.r.t that of minimum bias. When the relative $\langle p_T \rangle$ of J/ψ has been compared with measurements at $\sqrt{s} = 5.02$, as like the behavior of relative yield, center-of-mass energy independent scenario has been observed and can be clearly seen from the Fig. 4.36.

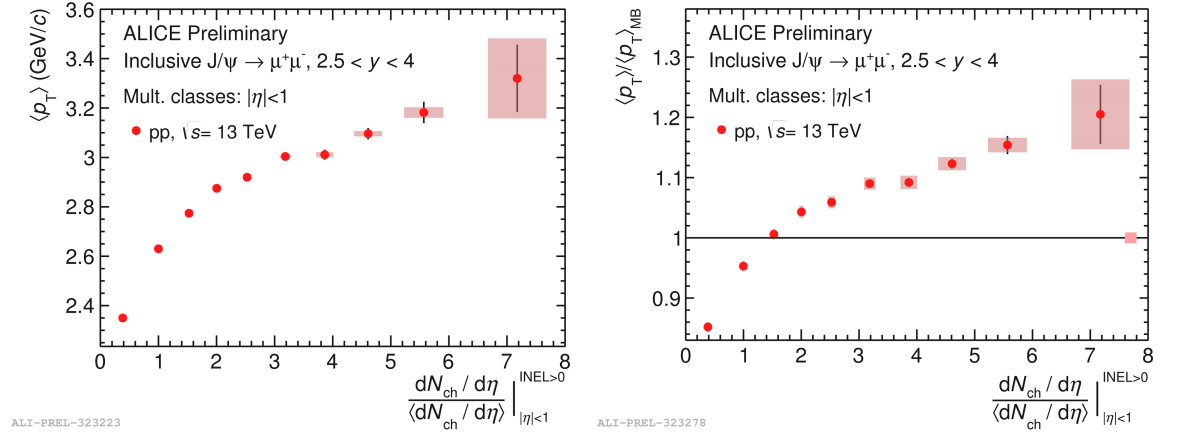


Figure 4.35. Forward-rapidity mean transverse momentum of J/ψ as a function of self-normalized charged-particle multiplicity for pp collisions at $\sqrt{s} = 13$ TeV [116, 129, 130].

An equal increase of value of $\langle p_T \rangle$ with collision energy at fixed values of $N_{ch}/\langle N_{ch} \rangle$ has been observed. This can be clearly seen from the left hand side of Fig. 4.36. The value of $\langle p_T \rangle$ for minimum bias collision at $\sqrt{s} = 5.02$ and 13 TeV are $2.367 \pm 0.033 \pm 0.008$ and $2.768 \pm 0.004 \pm 0.002$, respectively. Therefore, the $\langle p_T \rangle$ for $\sqrt{s} = 13$ TeV is around 1.15 times that of $\sqrt{s} = 5.02$ TeV, irrespective of the chosen multiplicity range. This is the reason, the relative $\langle p_T \rangle$ is found to be independent of center-of-mass energy. To have an idea about the nature of the trend, we have fitted the $\langle p_T \rangle$ of J/ψ as a function of multiplicity with the phenomenological function, $f(x) = [a - \frac{b}{(c+x)}]$ which is used to describe the $\langle p_T \rangle$ of light-flavor particle. It can be clearly seen from the Fig.4.36 that trend is well described by the function.

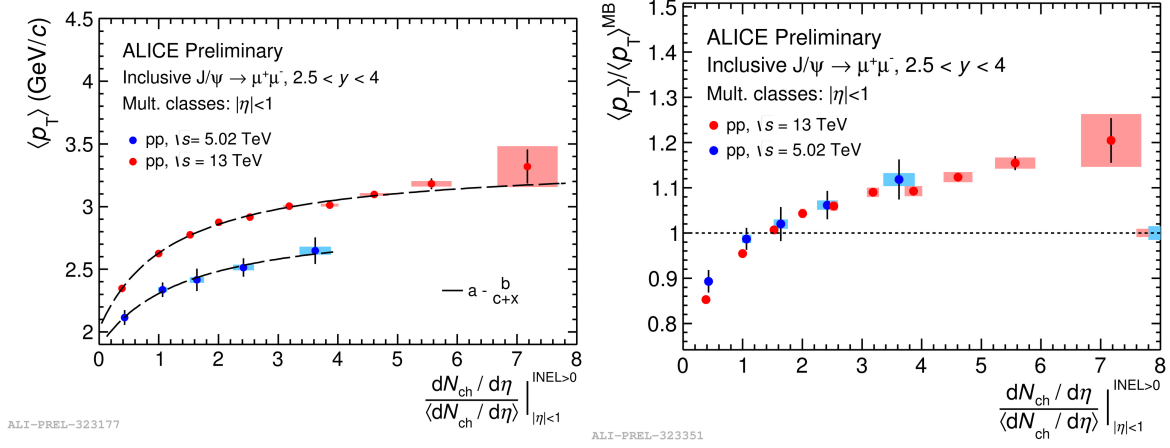


Figure 4.36. Forward-rapidity mean transverse momentum of J/ψ as a function of self-normalized charged-particle multiplicity for pp collisions at $\sqrt{s} = 5.02$ and 13 TeV [116, 129, 130]. The dashed line represents a phenomenological function, $f(x) = [a - \frac{b}{c+x}]$.

To have an idea, it is fair enough to compare the results of $\langle p_T \rangle$ with the $\langle p_T \rangle$ measured for p–Pb collisions and $\langle p_T \rangle$ of charged-particle measured by ALICE. It can be seen from the Fig. 4.37 that the trend saturates to 1 beyond relative $N_{ch} \approx 1.2$, for p–Pb collisions. This may be due to cold nuclear (CNM) effect or may be due to collectivity and the trend is more or less like that of $\langle p_T \rangle$ of charged-particle for Pb–Pb collisions [64]. But, for pp collisions, the trend is similar to p–Pb collisions up to $N_{ch} \approx 1.2$, and beyond, p–Pb saturates faster than pp as like charged-particle. The trend of $\langle p_T \rangle$ of J/ψ in pp collisions is like that of $\langle p_T \rangle$ of charged-particle for p–Pb collisions rather than pp, where a sharp increase of $\langle p_T \rangle^{ch}$ has been observed with saturation towards higher multiplicities [64]. The early saturation of $\langle p_T \rangle$ of J/ψ as compared to $\langle p_T \rangle^{ch}$ need to be understood. The theoretical investigation of the observed pictures of multiplicity dependence of $\langle p_T \rangle$ of J/ψ is ongoing and we believe that study will provide further insight into the underlying physics processes.

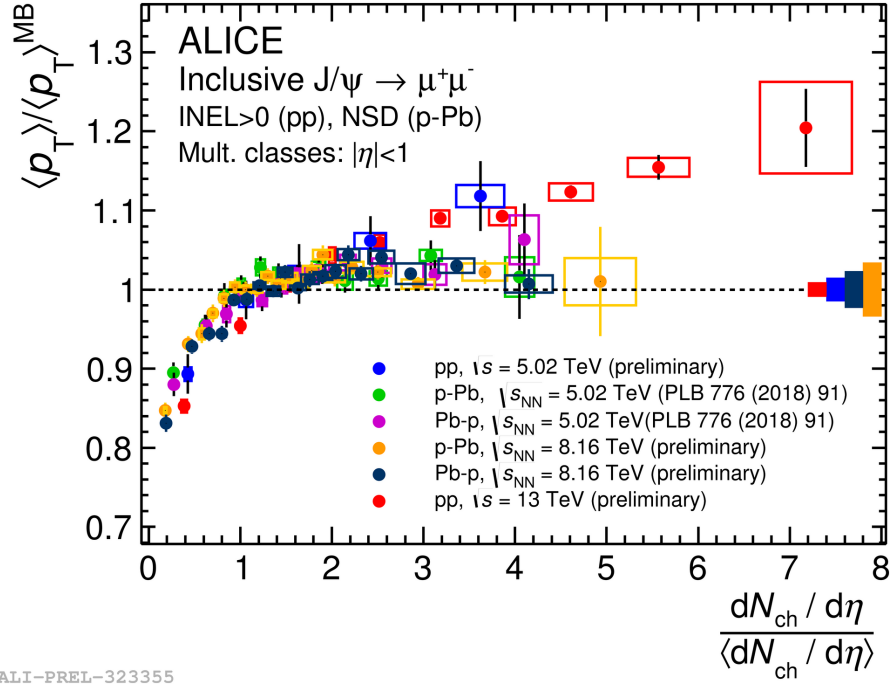


Figure 4.37. Self-normalized mean transverse momentum of J/ψ as a function of self-normalized charged-particle multiplicity for pp collisions at $\sqrt{s} = 5.02$ and 13 TeV, and is compared with the measurements of p–Pb collisions at $\sqrt{s_{NN}} = 5.02$ and 8.16 TeV [116, 130].

Chapter 5

Role of multipartonic interactions in J/ψ production

In order to understand the physics behind high-multiplicity pp collisions, we have performed several studies using the PYTHIA8 event generator ¹. PYTHIA8 contains a complex physics model with different processes implemented at different stages of the space-time evolution of pp collisions. Proton-proton collisions contain one or more perturbative scattering processes between the incoming partons implemented within the Multiple Partonic Interaction (MPI) framework [63]. The perturbative scattering processes are accompanied by Initial-State Radiation (ISR) and Final-State Radiation (FSR). The number of interactions per collision depends on the area of overlap in the collisions and, hence, on the pp impact parameter. Therefore, the probability for MPI to occur will increase towards smaller impact parameters. In MPI prospective, several studies have been done to understand the possibility of more than one hard interaction (higher p_T transfer) in an event theoretically and their effects have been observed by several experiments [135, 136]. At the final state, hadronization is implemented according to the Lund string fragmentation model [137]. The created partons and the beam-remnants are connected via colour flux tubes (strings storing potential energy). As the partons move apart, the string breaks, producing light quark-antiquark pair. The created partons and the beam-remnants are connected via colour flux-tubes. The process is repeated until the string become small enough in size which are finally identified as hadrons. PYTHIA8 implements the MPI based Color Reconnection

¹PHYSICAL REVIEW D97,094002 (2018), **Dhananjaya Thakur**, Sudipan De, Raghunath Sahoo, and Soumya Dansana

(CR) which works on the principle that the partons from two different MPIs can reconnect via color strings with the minimization of the string length. The reduction of the total string length leads to the reduction of the total multiplicity. We have investigated that CR together with MPI can produce our observations from the experimental data analysis. Further, the current study using PYTHIA8 allows us to extend the analysis where experimental measurements do not exist. Therefore, with the use of PYTHIA8, we have performed a more differential study of multiplicity as well as center-of-mass energy dependence of J/ψ production.

Recently, ALICE experiment has observed an approximately linear increase of relative J/ψ yields $\frac{dN_{J/\psi}/dy}{\langle N_{J/\psi}/dy \rangle}$ as a function of relative charged particle multiplicity density $\frac{dN_{ch}/dy}{\langle dN_{ch}/dy \rangle}$ [65]. The QCD inspired model PYTHIA6 could not describe the results and shows an exactly opposite behaviour. PYTHIA8 describes the increasing trend of open charm and non-prompt J/ψ production as a function of charged particle multiplicity measured by ALICE experiment at $\sqrt{s} = 7$ and 13 TeV [138, 139]. CR is expected to occur at a significant rate at LHC energies because of high number of colored partons from both MPI and parton showers. CR is the most important ingredient to the UE contributions and hence plays an important role in the interplay between soft and hard processes. As there is no first principle calculation, the only way is to study its effect via realistic models. It is found that PYTHIA8 describes the $\langle p_T \rangle$ as a function of charged particle multiplicity by including the MPI with-CR [140] as well as explains the flow like pattern in pp collisions [68]. In this work, we have studied the effect of MPI with and without-CR scheme on J/ψ production as a function of charged particle multiplicity using 4C tuned [141] PYTHIA8 event generator at different LHC energies. In the present work, for the first time we have studied the energy dependence of the event activity of J/ψ , which can provide more insight into the processes in an event in hadronic collisions.

This part of the thesis is organized as follows. Event generation and Analysis methodology is described in Section 5.1. The results are discussed in Section 5.2. The Section III is divided into three subsections. Multiplicity dependence of J/ψ production is discussed in subsection 5.2.1. In subsection 5.2.2,

we show the energy dependence behaviour and in subsection 5.2.3, we study the ratio between higher resonance state of J/ψ ($\psi(2S)$) and J/ψ as function of charged particle multiplicity. Finally, a brief summary of the work is given in the in section 5.3.

5.1 Event generation and Analysis methodology

PYTHIA8 is the advanced version of PYTHIA6 coded in C++. One of the major improvements in PYTHIA8 with respect to PYTHIA6 is the implementation of MPI scenario, where c and b quarks can be produced via $2 \rightarrow 2$ hard sub-processes. The heavy-flavor production in PYTHIA8 includes the following main processes:

1. initial c or b quarks originate via first hardest $2 \rightarrow 2$ partonic interactions (e.g: $q\bar{q} \rightarrow c\bar{c}$, $g\bar{g} \rightarrow c\bar{c}$) and also have the finite production probability from the subsequent hard processes in MPI via the same mechanism,
2. heavy quarks from gluon splitting hard processes (e.g: $g \rightarrow c\bar{c}$), and
3. these gluons may originate from initial and final state radiation (ISR/FSR).

Detailed explanation on PYTHIA8.2 physics processes can be found in Ref. [67]. At the LHC energies, it is possible to have multiple parton-parton interaction (MPI) in $p + p$ collisions. Many of the models have included it in different ways to explain the LHC $p + p$ data [142–144]. In our present study, we have used 4C tuned PYTHIA8.2. We have included varying impact parameter (Multi-partonInteractions:bProfile=3) to allow all incoming partons to undergo hard and semi-hard interactions as well. We have used the MPI-based scheme of Colour Reconnection (ColourReconnection:mode(0)) of PYTHIA8.2. In this scheme, the produced partons are classified by the MPI system that undergoes a reconnection where partons from lower p_T MPI systems are added to the

dipoles defined by the higher p_T MPI system such a way that minimizes total string length. This model of CR describes the underlying event observables very well compared to the other models as is reported by the ATLAS Collaboration in Ref. [145]. More details on various models of CR included in PYTHIA8.2 and their performances with respect to experimental data can be found in Refs. [64, 146]. After colour reconnection, all the produced partons, connected with strings, fragment into hadrons via the Lund String Model [137, 147].

In this study, we have simulated inelastic, non-diffractive component of the total cross section for all hard QCD processes (HardQCD:all=on), which includes the production of heavy quarks. A p_T cut off at 0.5 GeV/c (using PhaseSpace:pTHatMinDiverge) is used to avoid the divergences of QCD processes in the limit $p_T \rightarrow 0$. J/ψ production is measured in the dimuon channel. We have specifically decayed J/ψ to the dimuon channel and measured the yield of the reconstructed particles by defining an external decay mode.

We have generated 100 million events for $p + p$ collisions at $\sqrt{s} = 0.9, 2.76, 5.02, 7$ and 13 TeV using the option with-CR and without-CR scheme available in PYTHIA8.2. J/ψ are reconstructed via dimuon channel ($J/\psi \rightarrow \mu^+ + \mu^-$). The charged particle multiplicity yield, which is defined as $N_{ch}/<N_{ch}>$, is measured at midrapidity ($|y| < 1.0$), where N_{ch} is the mean of the charged particle multiplicity in a particular bin and $<N_{ch}>$ is the mean of the charged particle multiplicity in minimum-bias events. The relative J/ψ yield is measured in forward rapidity ($2.5 < y < 4.0$) using the following relation:

$$\frac{Y_{J/\psi}}{<Y_{J/\psi}>} = \frac{N_{J/\psi}^i}{N_{J/\psi}^{total}} \frac{N_{evt}}{N_{evt}^i}, \quad (5.1)$$

where, $N_{J/\psi}^i$ and N_{evt}^i are the number of J/ψ and number of events in i^{th} multiplicity bin, respectively. $N_{J/\psi}^{total}$ and N_{evt} are the total number of J/ψ produced and total number of minimum-bias events, respectively. As the frequency of lower multiplicity events is higher, the bin width is taken smaller at lower multiplicity and then subsequently higher to maximize the statistics at high multiplicity bins. To have a direct comparison of the obtained results with experimental data, charged particle multiplicity bins are chosen according to

the available experimental measurements [65].

The statistical uncertainties are calculated in each multiplicity bin for both relative charged particle multiplicity ($N_{ch}/\langle N_{ch} \rangle$) and relative J/ψ yield ($N_{J/\psi}/\langle N_{J/\psi} \rangle$). Uncertainty in N_{ch} measurement is given by the ratio of RMS value of the charged particle multiplicity and square root of the number of charged particles in that bin ($N_{RMS}/\sqrt{N_{bin}}$). The ratio between RMS value of the minimum-bias (MB) charged particle multiplicity and square root of the number of minimum-bias charged particles ($N_{RMS}^{MB}/\sqrt{N_{MB}}$) gives the uncertainty in $\langle N_{ch} \rangle$. The uncertainty to measure the number of J/ψ particles is simply $\sqrt{N_{J/\psi}}$. These uncertainties are propagated using standard error propagation formula to estimate the uncertainties in relative charged particles multiplicity as well as in relative J/ψ yield.

5.2 Results and Discussion

To check the compatibility of PYTHIA8 with the experimental data we have compared J/ψ production between data and PYTHIA8 in same kinematic range. Fig. 5.1 show the comparison of J/ψ production cross-section as a function of p_T and rapidity (y), respectively between data and PYTHIA for minimum-bias events. The open symbols represent the data obtained from ALICE and the solid circles and stars show the results from PYTHIA8 model at $\sqrt{s} = 5.02$ TeV [148]. The lower panels of the figures show the ratio between data and model for both CR and No-CR cases. It is observed that the PYTHIA8 explains the data very well. Similar study has been performed in other available LHC energies. We found a maximum of 60% deviation of MC p_T spectra from data for 13 TeV in certain p_T bins except for two low- p_T bins ($p_T \sim 1$ GeV/c), where deviation is larger. For the rapidity spectra, the deviation of MC from experimental data is less than 1%. Similarly, for 7 TeV, 5.02 TeV and 2.76 TeV, the maximum deviation of (p_T, y)-spectra are (50%, 1%), (1%, 1%) and (50%, 1%), respectively for few p_T and rapidity bins. In most of the p_T bins, the deviation is around 10-20%, whereas rapidity spectra are very well reproduced by MC. These measurements provide us the confidence

to study the quarkonia production using PYTHIA8 in $p + p$ collisions at LHC energies.

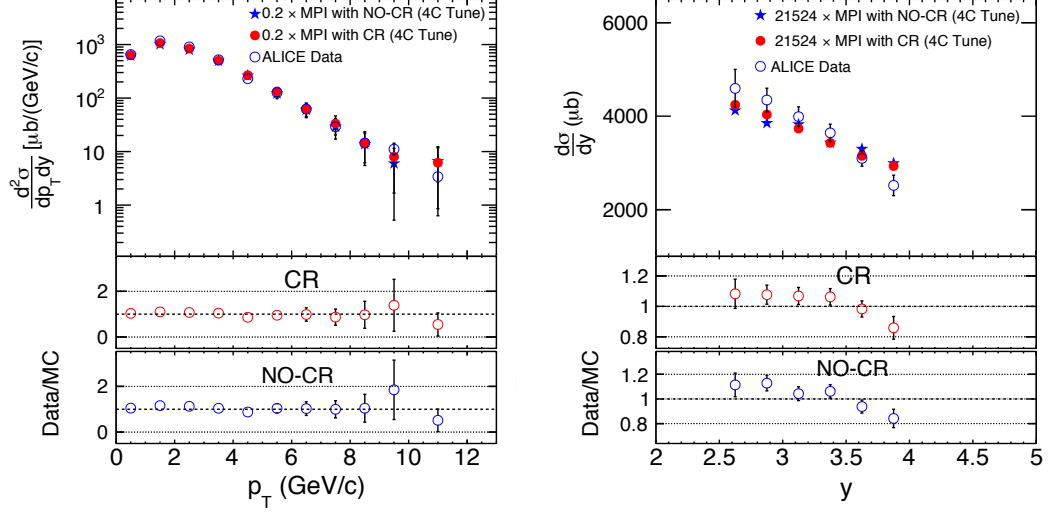


Figure 5.1. (Color online) **Left:** Upper panel shows the comparison of ALICE data [65] and PYTHIA8 of J/ψ production cross-section at $\sqrt{s} = 5.02$ TeV. The open circles are ALICE data and solid circles and stars represent PYTHIA8 results with-CR and without-CR, respectively. Lower panels show the ratio between data and PYTHIA8 for both CR and NO-CR cases. **Right:** Upper panel shows the comparison of ALICE data [65] and PYTHIA8 for $d\sigma/dy$ of J/ψ at $\sqrt{s} = 5.02$ TeV. The open circles are ALICE data and solid circles and stars represent the PYTHIA8 results with-CR and without-CR, respectively. Lower panels show the ratio between data and PYTHIA8 for both CR and NO-CR cases [149].

Figure 5.2 shows the relative J/ψ yield as a function of charged particle multiplicity for $\sqrt{s} = 7$ TeV. The open circles show the results from ALICE experiment [65]. The star markers and solid circles represent our measurement with PYTHIA8. It is observed that 4C tuned PYTHIA8 with-CR and without-CR qualitatively reproduce the ALICE results. In the experimental data there were statistical and systematic uncertainties. We have added both the errors in quadrature and put single error bar in each data point. The PYTHIA8 data points have statistical uncertainties which are obtained using the method described in the previous section. Direct comparison of data to PYTHIA is not possible as the $N_{ch}/\langle N_{ch} \rangle$ values are different for different cases. So, we have fitted the results obtained from PYTHIA8 model using a percolation inspired function [150] as described in next section and interpolated the relative

J/ψ yield at the experimental $N_{ch}/\langle N_{ch} \rangle$ values to make the ratio between data and PYTHIA. From the ratio it is clear that PYTHIA8 explains the data well for both CR and NO-CR cases.

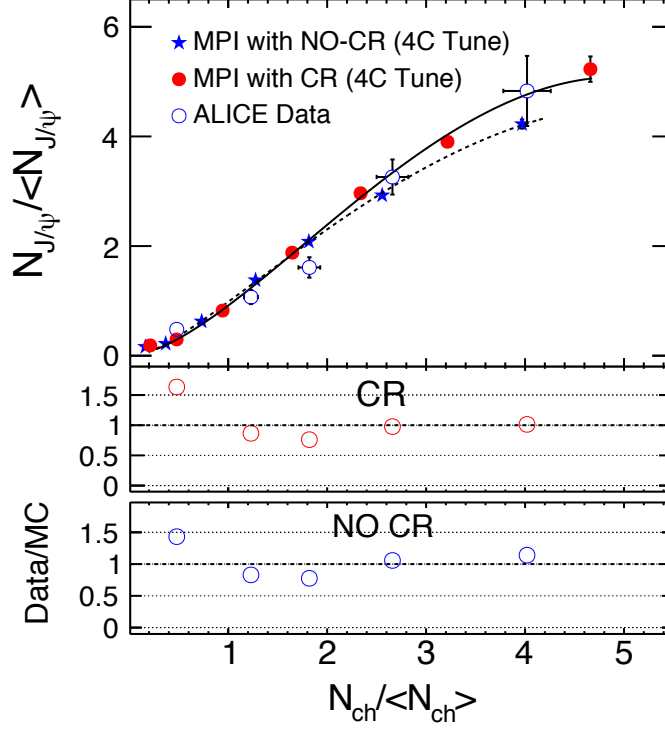


Figure 5.2. (Color online) Upper panel shows the comparison of ALICE data [65] and PYTHIA8 of relative J/ψ yield ($N_{J/\psi}/\langle N_{J/\psi} \rangle$) as a function of the relative charged particle multiplicity ($N_{ch}/\langle N_{ch} \rangle$) for $\sqrt{s} = 7$ TeV at forward rapidities. The open circles are ALICE data and solid circles and stars represent the PYTHIA8 results with-CR and without-CR, respectively. The lines are the fitted curves using the function as described in Eq. 5.2. Lower panels show the ratio between data and PYTHIA for both CR and NO-CR cases [149].

The color reconnection is a final state effect, which takes place in $p + p$ collisions as implemented in PYTHIA8 [67]. In our current studies, we use the MPI-based color reconnection, and it is observed that the difference in number of J/ψ in CR and NO-CR is less than one per event. However, in highest two multiplicity bins the differences are higher. A quantitative study is performed in the next section. Therefore, one can conclude that the final state effect (CR) has little contribution to J/ψ production. Although both CR and NO-CR describe experimental data well within the uncertainties, it is found that towards the higher multiplicity bins, MPI with-CR seems to reproduce the data

better than that of MPI with NO-CR case.

To explore the effect of MPI on quarkonia production with collision energies, we extend the analysis using PYTHIA8 to other available energies at the LHC.

5.2.1 Multiplicity dependence of J/ψ production

Figure 6.7 shows the relative J/ψ yield as a function of relative charged particle multiplicity at forward rapidity ($2.5 < y < 4.0$) for 4C tuned with and without CR at $\sqrt{s} = 0.9, 2.76, 5.02, 7$ and 13 TeV using the PYTHIA8 simulated data. The J/ψ are reconstructed via dimuon channel. The circles show the results with-CR scheme and the stars show the results without-CR. It is observed that the relative J/ψ yield is linearly increasing with charged particle multiplicity for all the centre-of-mass energies for both with and without-CR cases. We have fitted the results with a percolation inspired function [150]. It is found that the function itself can not describe the results well unless we add an extra term x^n in the function:

$$\frac{Y_{J/\psi}}{\langle Y_{J/\psi} \rangle} = A[Bx + Cx^2 + Dx^n], \quad (5.2)$$

where A, B, C, D and n are the parameters and $x = N_{ch}/\langle N_{ch} \rangle$. The solid lines show the fitting results with-CR and the dashed lines show the fitting results without-CR. The difference between solid line and dashed line increases with higher multiplicity bins as well as with higher centre-of-mass energies, in particular, at $\sqrt{s} = 7$ and 13 TeV. This indicates that the CR effects on J/ψ production is more prominent at high multiplicity region of higher centre-of-mass energies.

Till now, the percolation theory has been successful in describing the relative J/ψ yield as a function of relative charged particle multiplicity [150]. To see if a string percolation scenario of particle production in $p+p$ collisions is valid at the highest available energy, *i.e.* at $\sqrt{s} = 13$ TeV, we take PYTHIA8 simulated data in our current study. We compare string percolation model

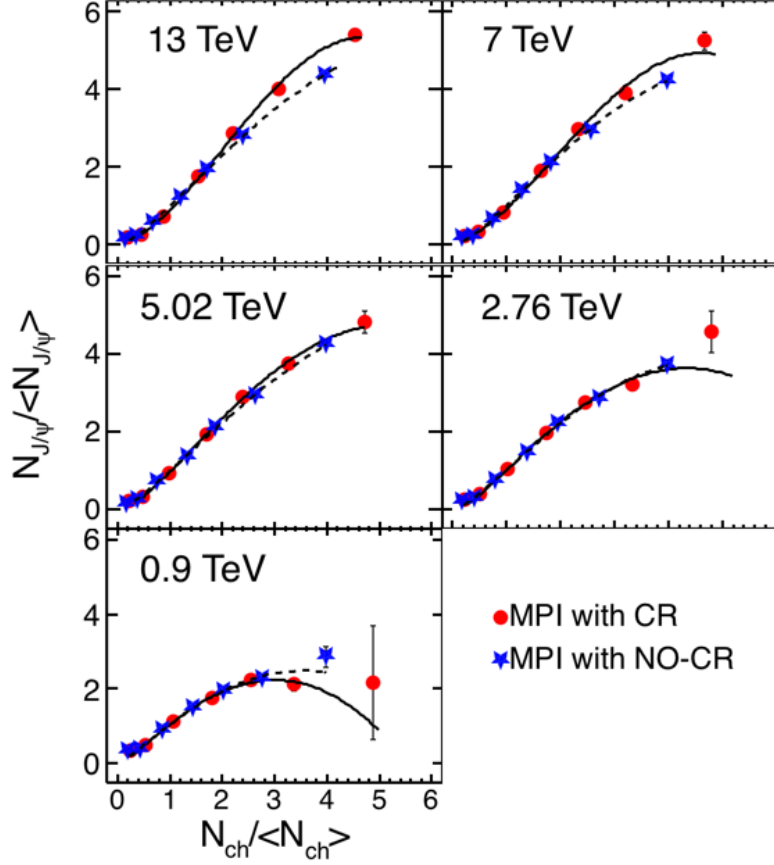


Figure 5.3. (Color online) Relative J/ψ yield as a function of relative charged particle multiplicity at forward rapidities at $\sqrt{s} = 0.9, 2.76, 5.02, 7$ and 13 TeV using PYTHIA8. The circles and stars show the results with-CR and without-CR, respectively. The dotted line is fitted to MPI with NO-CR using Eq. 5.2, whereas the solid line represents the fitting to MPI with-CR using Eq. 5.2 [149].

expectations using the function $f(x) = Ax + Bx^2$ and found a deviation at large multiplicity bins, where a kind of saturation behaviour is seen in PHYTHIA8. An additional term in the above equation, x^n seems to describe the behaviour. This is shown in Fig. 6.8. This study shows that the increase of J/ψ yield as a function of charged particle multiplicity from PYTHIA simulated data doesn't seem to follow exactly like a percolation type of behaviour rather a tendency to saturate at high multiplicity domain. The $p + p$ experimental data at other LHC energies would be very useful in understanding the particle production at higher multiplicities, helping to validate the percolation theory and/or tuning the PYTHIA8 event generator with new physics inputs.

To understand the CR effects on J/ψ production quantitatively, we have subtracted the yield of relative J/ψ production with no-CR from the yield

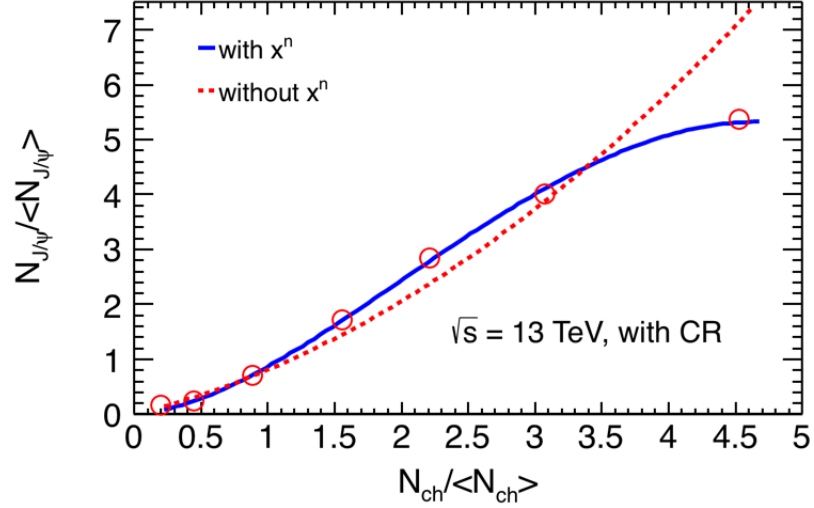


Figure 5.4. (Color online) Relative J/ψ yield as a function of the relative charged particle multiplicity for $p + p$ collisions at $\sqrt{s} = 13$ using PYTHIA8 with-CR. The phenomenological function given by Eqn. 5.2 without the term x^n is fitted to understand the validity of string percolation. This is shown by the dotted line. The solid line shows the fitting using Eq. 5.2, which has an additional term, x^n over the string percolation function. This explains a possible saturation effect towards higher multiplicities [149].

with-CR and plotted as a function of charged particle multiplicity for different centre-of-mass energies, which is shown in Fig. 5.5. It is found that the difference of relative J/ψ yield between with-CR and without-CR increases as a function of charged particle multiplicity as well as with increase of centre-of-mass energy. The excess values of relative J/ψ are shown in the Table 6.1 for different multiplicity bins at all the discussed energies. We could not perform our studies at lower centre-of-mass energies for higher multiplicity bins due to higher statistical fluctuations. Although the numbers are very small, they are

N_{ch} bin	$\sqrt{s} = 0.9$ TeV	$\sqrt{s} = 2.76$ TeV	$\sqrt{s} = 5.02$ TeV	$\sqrt{s} = 7$ TeV	$\sqrt{s} = 13$ TeV
0-5	0.019 ± 0.026	0.024 ± 0.016	0.059 ± 0.013	0.025 ± 0.013	0.020 ± 0.011
5-10	0.108 ± 0.018	0.088 ± 0.012	0.063 ± 0.011	0.077 ± 0.010	0.052 ± 0.009
10-20	0.236 ± 0.025	0.260 ± 0.020	0.217 ± 0.019	0.197 ± 0.018	0.129 ± 0.017
20-30	0.239 ± 0.046	0.505 ± 0.042	0.558 ± 0.041	0.500 ± 0.041	0.535 ± 0.038
30-50	0.314 ± 0.091	0.553 ± 0.075	0.768 ± 0.070	0.881 ± 0.070	0.938 ± 0.066
50-100	-	-	0.840 ± 0.101	0.975 ± 0.095	1.233 ± 0.083
100-150	-	-	-	1.001 ± 0.246	1.017 ± 0.161

Table 5.1. The difference values of relative J/ψ with-CR and without-CR, $(N_{J/\psi} / <N_{J/\psi}>)_{\text{CR-NoCR}}$ for $\sqrt{s} = 0.9, 2.76, 5.02, 7$ and 13 TeV [149].

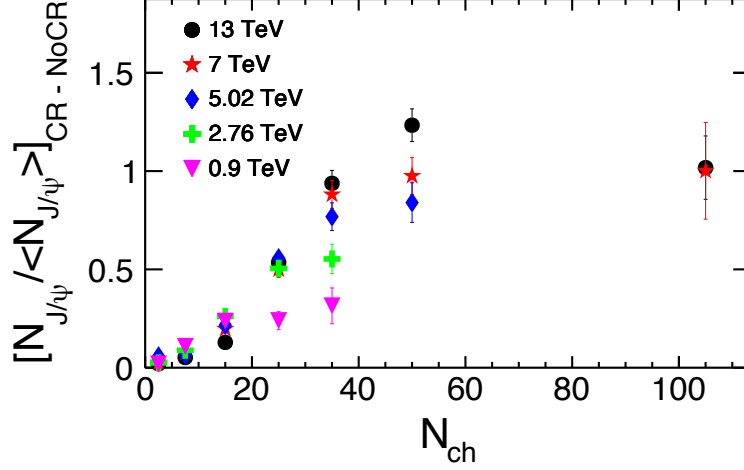


Figure 5.5. (Color online) Difference of relative J/ψ yield from MPI with-CR to MPI without-CR as a function of the charged particle multiplicity at $\sqrt{s} = 0.9, 2.76, 5.02, 7$ and 13 TeV using PYTHIA8 [149].

very significant as the J/ψ yield is measured in event-by-event basis and normalised with total MB events using Eq. 6.2. It should be noted that the relative J/ψ yield is the excess of J/ψ production per event in a given multiplicity bin with respect to J/ψ per event in MB.

It is expected that CR occurs in a significant rate at the LHC energies due to higher number of colored partons from MPI. In our current study, we have used the default MPI based CR. Here, partons from lower p_T MPI are merged with the ones at higher p_T MPI [151]. At LHC energies due to high density of colored partons, there is a substantial degree of overlap of many colored strings in the position and momentum phase space. Therefore, there is higher probability of color reconnection. The partons from two different MPIs can reconnect via color strings with the minimization of the string length. This study reveals that with increase of MPI, the probability of color reconnection increases and hence the probability to combine charm and anti-charm quark becomes higher thereby producing higher number of J/ψ particles. Further, the little effect of final state process like CR on heavy flavor yields suggest the MPI origin of high multiplicity events. Heavy quarks (c, b) are created in hard processes with a minimum momentum transfer of $Q > 2m_Q \gg \Lambda_{QCD}$ and they are very rarely created during hadronization of a different parton species.

5.2.2 Energy dependence of J/ψ production

As experimental data at different energies are not yet available, it is worth studying the effect of MPI and CR on charmonia production at various collision energies using PYTHIA8. The left panel of figure 6.6 shows the relative J/ψ yield as a function of centre-of-mass energy for different charged particles multiplicity bins using PYTHIA8 with-CR. It is observed that for higher multiplicity bins the relative J/ψ production increases with energy and the trend changes as we go to lower multiplicity bins. To get a quantitative idea, we have fitted the results with a phenomenological function, $y = Ax^n$, where A and n are the parameters. The parameter, n indicates the rate of increase of relative J/ψ as a function of centre-of-mass energy for a particular multiplicity bin. The right panel of figure 6.6 shows n as a function of multiplicity. It is found that n increases with the increase in charged particle multiplicity (N_{ch}). The values of n are negative up to 10-20 multiplicity bins and becomes positive towards higher multiplicity bins. This indicates that MPI effects dominate for J/ψ production for $N_{ch} > 20$. This brings a threshold number for charged particle multiplicity in the final state for $p + p$ collisions in order to observe substantial MPI effects on charmonia production.

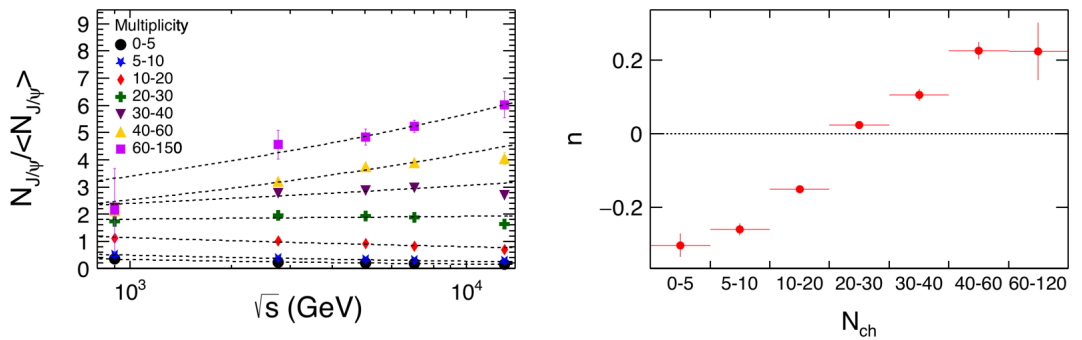


Figure 5.6. (Color online) **Left:** Relative J/ψ yield as a function of centre-of-mass energy, ($\sqrt{s}$) using PYTHIA8 with-CR. Different symbols are for different charged particle multiplicity bins. The dashed lines are the phenomenological fitting using the function, $y = Ax^n$. **Right:** The fitting parameter, n , for different multiplicity bins [149].

5.2.3 Ratio of $\psi(2S)$ and J/ψ

As $\psi(2S)$ is the first excited state of J/ψ , we have made an attempt to study the ratio of both as a function of charged particle multiplicity for different collision energies. Same procedure for the reconstruction of $\psi(2S)$ is followed as is done for J/ψ , which is discussed in previous sections. Figure 5.7 shows the multiplicity dependence of the ratio of relative yield of $\psi(2S)$ to J/ψ using PYTHIA8 MPI with-CR. It is interesting to see that the ratio is independent of collision energy as well as multiplicity within statistical uncertainties. The energy independent behaviour of the ratio of relative yields of $\psi(2S)$ to J/ψ is also supported by color evaporation models [152]. At LHC energies, there are sufficient energies to produce $c\bar{c}$ and as the mass difference between the two charmonia states is smaller compared to the collision energy, the production probability would be similar for both the cases in each multiplicity bin. This could be the reason of energy and multiplicity independent behaviour of the ratio of relative yields of $\psi(2S)$ to J/ψ . The CMS experiment preliminary results also show a similar trend at $\sqrt{s} = 7$ TeV [153].

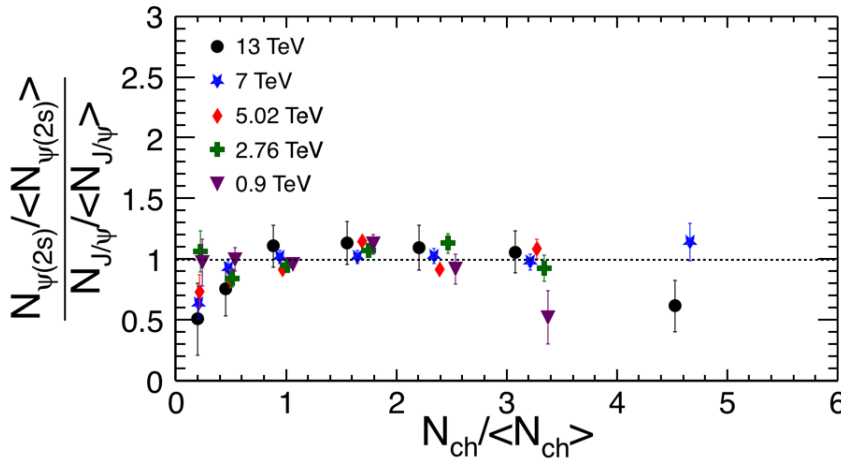


Figure 5.7. (Color online) Ratio of the relative yields of $\psi(2S)$ and J/ψ as a function of relative multiplicity for different centre-of-mass energies ($\sqrt{s}$) using PYTHIA8 MPI with-CR [149].

From Eq. 6.2 we can write the relative ratio of $\psi(2S)$ to J/ψ as:

$$\frac{Y_{\psi(2S)}/<Y_{\psi(2S)}>}{Y_{J/\psi}/<Y_{J/\psi}>} = \frac{N_{\psi}^{total}}{N_{J/\psi}^{total}} \frac{N_{J/\psi}^i}{N_{\psi}^i} \quad (5.3)$$

Here, the ratio $N_{\psi}^{total}/N_{J/\psi}^{total}$ is fixed for a particular collision energy. This implies that the $\psi(2S)$ and J/ψ in each multiplicity bin are almost produced in same proportion within statistical uncertainties. This requires further investigations for a clear understanding of the underlying physics mechanism(s). The availability of experimental data in the near future will make the scenario more clear.

5.3 Summary

In summary, energy dependent study of J/ψ production as a function of charged particle multiplicity has been performed using 4C tuned PYTHIA8 MC event generator. The relative J/ψ are measured as a function of charged particle multiplicity in $p+p$ collisions at $\sqrt{s} = 0.9, 2.76, 5.02, 7$ and 13 TeV. The J/ψ are reconstructed via dimuon channel at forward rapidity ($2.5 < y < 4.0$), whereas the charged particles are measured at mid-rapidity region ($|y| < 1$). PYTHIA8 simulated data are generated using with-CR and without-CR. It is found that both the tunes explain the ALICE data qualitatively for $p+p$ collisions at $\sqrt{s} = 7$ TeV. A detailed quantitative study is performed to understand the CR effects on MPI for J/ψ production. We observed that the difference between CR and No-CR increases with charged particle multiplicity as well as with centre-of-mass energy. The CR effects mostly dominate at high multiplicity bins for $\sqrt{s} = 7$ and 13 TeV. The relative J/ψ yield as a function of $\sqrt{s}$ shows a monotonic increase for higher multiplicity bins, whereas for bins with $N_{ch} \leq 20$, it shows an opposite behaviour. This brings a threshold number for charged particle multiplicity in the final state for $p + p$ collisions in order to observe substantial MPI effects on charmonia production. This is a very important observation in view of the interesting properties shown by high multiplicity events in $p+p$ collisions at the LHC energies. The ratio of relative yield between $\psi(2S)$ and J/ψ is measured

at all centre-of-mass energies are presented as a function of relative charged particle multiplicity. $\psi(2S)$ to J/ψ ratio shows both energy and multiplicity independent behaviour. It will be very interesting to get the experimental measurements, which can help to understand the production mechanism of charmonia states in $p + p$ collisions.

Study of Particle Production in High-Energy Collisions

In the previous chapters, so far the discussion was on the multiplicity dependence of J/ψ production, which helps us to explore the QCD system formed in high multiplicity pp collisions. Hence, this will provide necessary inputs to the understanding of J/ψ suppression in heavy-ion collisions: a most reliable observable to understand the formation of QGP. In this chapter, we have try to explore the other aspects of the high energy collisions; such as phase transition and the freeze-out properties. These studies will help us to give a complete picture of the high energy collisions: starting from probing the initial state through the study of J/ψ production to the understanding of the phase transition by higher order cumulant of conserved numbers, then to explore the freeze-out properties by using statistical models.

In the past decades, the experimental results of heavy ion collisions at both RHIC and LHC energies have been extensively studied. These studies have shown that the strongly coupled quark-gluon plasma (QGP) might be created in these collisions [70, 154–158]. Therefore, the deconfined quark-gluon plasma (QGP) system which is predicted by quantum chromodynamics (QCD) calculations can be investigated. The average multiplicities of particles produced in high-energy collisions are very useful tools to investigate it. These multi-particle production is especially related to the statistical properties of global observables, dynamical evolution of interacting system, various distributions and correlations. One of the main motivations of studying heavy-ion collisions is to explore the QCD phase diagram of the strong interaction, i.e to map the

quantum chromodynamics (QCD) phase diagram in terms of temperature (T) and baryon-chemical potential (μ_B). Lattice QCD calculations indicate that at vanishing μ_B , the transition from the QGP to a hadron gas is a smooth crossover, while at large μ_B , the phase transition is of first order [158–165]. The search for the QCD critical point (CP) is one of the main motivations behind the STAR (Solenoidal Tracker At RHIC) experiment at BNL. The recent net-proton fluctuation result by STAR experiment has predicted a CP around $\sqrt{s_{NN}} = 19.6$ GeV [166], where the inclusive protons have been considered for the analysis. Therefore, it is necessary to look into the dynamical behavior of the produced system by considering the observable effects of baryon stopping which could have a substantial contribution to the present result. In the first part of this chapter of the thesis, we have discussed a technique to quantify the stopping contribution to the STAR experimental result. Thereafter, in the second part, we describe the statistical-thermodynamical approach to the hadron production by using Tsallis non-extensive statistics and show how the thermodynamical quantities vary with center-of-mass energy, centrality, collision species as well as particle species.

6.1 Understanding of QCD phase diagram through baryon stopping

¹ Onset of deconfinement in relativistic heavy-ion collisions is a research frontier for theoretical and experimental studies of relativistic heavy-ion collisions. This problem is one of the main motivations for the beam-energy scan (BES) at the Relativistic Heavy-Ion Collider (RHIC) at Brookhaven National Laboratory (BNL) and low-energy-scan program of CERN, as well as newly constructed Facility for Antiproton and Ion Research (FAIR) in Darmstadt. All the experiments try to explore the QCD phase diagram at low energies (at finite μ_B and T). As discussed, theoretical studies reveal a first order phase transition of hadrons to QGP at finite μ_B and T with a critical end point. The divergence of

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thermodynamic quantities, such as correlation length, susceptibility and heat capacity (C_v) is expected at the CP. Theoretically, fluctuation of conserved quantities such as net baryon (B), electric charge (Q), strangeness (S) etc. are directly connected to susceptibilities. Therefore, the divergence of these experimental quantities is expected at the CP. STAR experiment has studied the energy and centrality dependence of the moment products $\kappa\sigma^2$ and $S\sigma$ of net-proton distribution, where kurtosis (κ) and skewness (S) are the non-Gaussian measures, and σ is the standard deviation. The observations of the STAR experiment is presented in Fig. 6.1. The observed structure is not reproduced by either non-CP transport model calculations or by hadron resonance gas model. The non-monotonic behavior of the moment products: $\kappa\sigma^2$ and $S\sigma$ hints for CP.

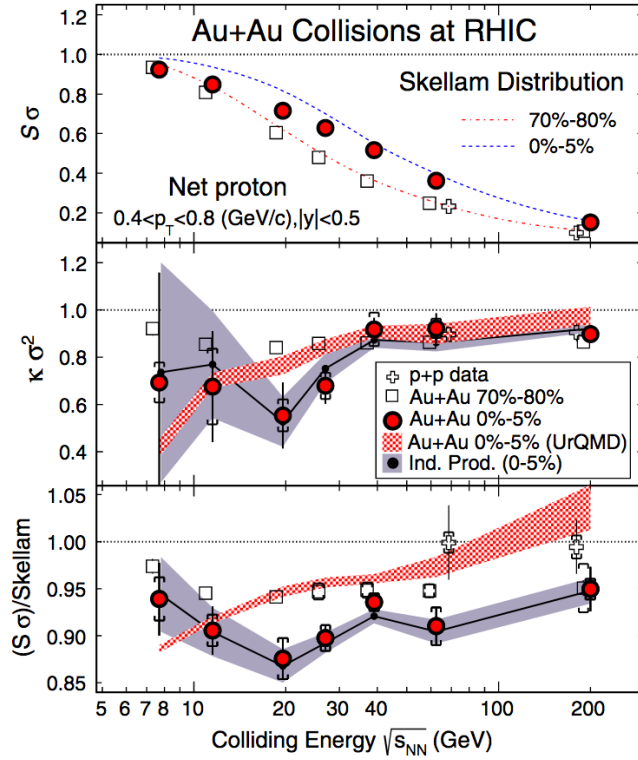


Figure 6.1. Collision energy and centrality dependence of the net proton $S\sigma$ and $\kappa\sigma^2$ from Au-Au and pp collisions at RHIC [166].

One can argue that at such low energies, baryon stopping in nuclear collision can be a sensitive probe of the onset of deconfinement. The phenomenon of baryon stopping could be used as a direct tool to explore the QCD phase tran-

sition and as a probe of the equation of state (EOS) of the system [170]. The kinetic energy that is removed from the beam and which is available for the production of a state such as the QGP depends on the amount of stopping between the colliding ions. The reduced curvature obtained from the net-proton rapidity distribution at the mid-rapidity, is used as an observable for the baryon stopping. As discussed in Ref. [170], the behaviour of the mid-rapidity curvature with $\sqrt{s_{NN}}$ has been studied and a zig-zag type of structure is observed which is shown in Fig. 6.2. A three-fluid dynamics (3FD) calculation with hadronic EoS fails to explain the observed structure, whereas 3FD with first order phase transition from a hadronic phase to a deconfined phase of quark-gluon plasma qualitatively reproduces the structure [170]. Hence, it is argued that the non-monotonic behavior of the baryon stopping is due to a phase transition and is most probably of first order in nature.

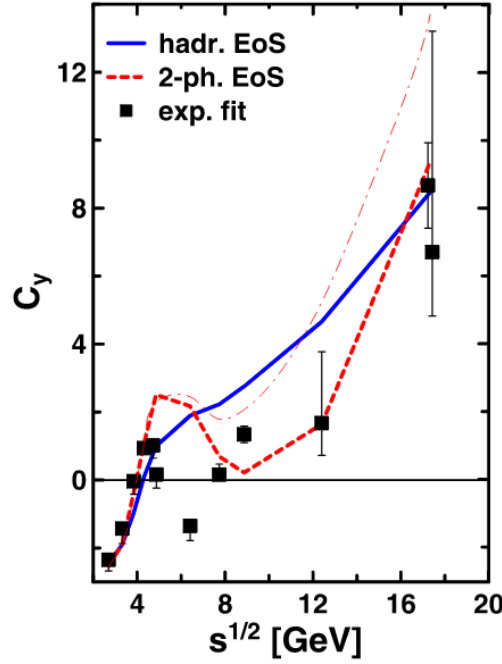


Figure 6.2. Mid-rapidity reduced curvature of the net-proton rapidity distribution as a function of the center-of-mass energy described by 3FD calculations with hadronic EoS (hadr. EoS) and a EoS involving a first-order phase transition into the quark-gluon phase (2-ph. EoS) [170].

Theoretical studies based on STAR net-proton fluctuation [166] hint for a phase transition at low $\sqrt{s_{NN}}$ with CP around $\sqrt{s_{NN}} = 19.6$ GeV, taking in-

clusive protons, *i.e.* from both production and stopping. However, at the same time, studies on baryon stopping reveals a possible first order phase transition. Therefore, it is worth looking for the role of baryon stopping in the observed structure by STAR experiment, as baryon stopping plays a major role at lower collision energies and almost vanishes at higher energies. It seems to be a need to disentangle the contribution of stopped baryons and the produced baryons in order to understand the observed structure and hence, the QCD phase diagram. The present work is motivated to study net-baryon (proton) number fluctuation, which is related to particle production mechanism. But, most of the experimentally measured proton distributions contain the protons from stopping and resonance decays besides from the direct production. Also, it has been studied earlier that the change in the mean of proton distributions (which will be there, after subtracting the stopped protons) will have large effect on the correlation of the protons and antiprotons, and it can influence the higher moments of net-protons fluctuations [175]. Particularly, at lower center-of-mass energies the stopping contribution is most dominant and it will be interesting to look for the dynamical fluctuations after removing these stopped protons.

The stopping can be estimated from the rapidity loss experienced by the baryons in the colliding nuclei. If incoming beam baryons have rapidity, $y_b = \ln(\sqrt{s_{NN}}/m_p)$ (m_p = mass of proton), then the average rapidity carried by the particles after the collisions is given by,

$$\langle y \rangle = \left(\int_0^{y_b} y \frac{dN}{dy} \right) / \left(\int_0^{y_b} \frac{dN}{dy} \right) \quad (6.1)$$

Where, dN/dy denotes the number of net-baryons per unit of rapidity. Therefore, the average rapidity loss is $\delta y = y_b - \langle y \rangle$. Hence, for *full stopping*; $\delta y = y_b$ and for *full transparency*; $\delta y = 0$. For the case of full stopping, the average rapidity carried by the particles, $\langle y \rangle = 0$ and for full transparency $\langle y \rangle = y_b$ *i.e.* the maximum of rapidity carried by the particles after the collisions. As baryon number is conserved, baryon stopping can be directly measured via the rapidity distribution of net-baryons (*i.e.* the number of baryons minus anti-baryons). Since neutrons are not measured in most of

the heavy-ion experiments, the net-proton rapidity distribution is used as a proxy to net-baryon rapidity distribution and is used to quantify the baryon stopping [172–174]. At low energies like AGS, the production of antiprotons is very small, so the net-proton distribution is assumed to be the same as the proton distribution and the rapidity distribution peaks at mid-rapidity [170]. As the collision energy increases, a dip begins to appear at mid-rapidity ($y \approx 0$) and the peak shifts towards the forward and backward rapidities, due to the production of antiprotons at mid-rapidity. This indicates that with increase of energy the transparency at the mid-rapidity increases. Fig. 6.3 is an example to illustrate the nature of baryon stopping with colliding energy.

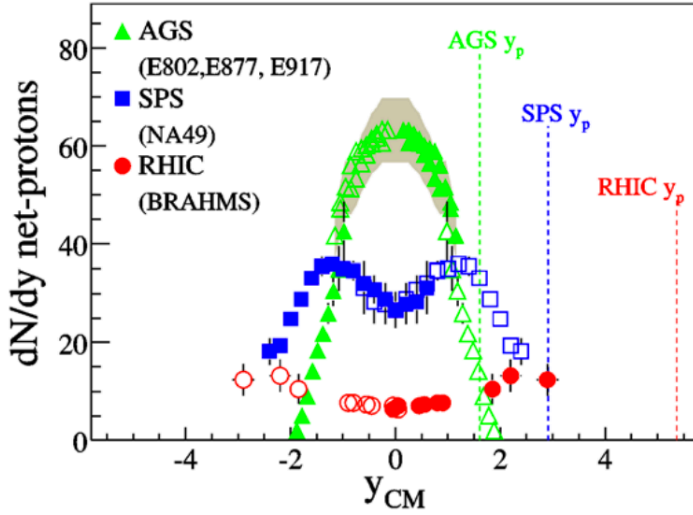


Figure 6.3. Rapidity density of net protons ($p - \bar{p}$) measured at AGS,SPS, and RHIC energies for central collisions [70].

For the work presented in this part of the thesis, we use the data of net-proton rapidity distributions for the most central Au-Au collisions measured at AGS, SPS and by the BRAHMS experiment at RHIC. We use a two source function [170] to analyze the net-proton distributions at different center-of-mass energies. It is a combination of two thermal sources with a shift in their rapidities. The same two source function is used in the present work to calculate the percentage of stopped protons. Afterwards, the percentage of stopped protons with $\sqrt{s_{NN}}$ is parametrized and the values at RHIC BES energies are interpolated. Finally, we estimate the contribution of stopped protons in rapidity,

$|y| < 0.5$ and transverse momentum between 0.4 GeV/c and 0.8 GeV/c, which are the kinematic limits used to measure the protons and antiprotons by STAR experiment for net-proton fluctuation studies [166].

6.1.1 Method

Estimation of baryon stopping in $|y| < 0.5$:

Net-proton rapidity distribution of the experimental data is best described by the following function:

$$dN/dy = a [\exp\{-(1/w_s) \cosh(y - y_{cm} - y_s)\} + \exp\{-(1/w_s) \cosh(y - y_{cm} + y_s)\}], \quad (6.2)$$

where a , y_s and w_s are the fit parameters of the function and y_{cm} is the center-of-mass rapidity of the colliding nuclei [170]. Eq. 6.2 is the sum of two thermal sources shifted by rapidity $\pm y_s$ from the mid-rapidity. w_s is the width of the sources and is given by $w_s = (\text{temperature})/(\text{transverse mass})$, with the assumption that there is no spread of collective velocities in the sources with respect to the source rapidities. We have used Eq. 6.2 to fit the net-proton rapidity distributions to quantify the baryon stopping. Since we are concerned about symmetric collisions, the parameters of the two sources are taken identical. Parameters y_s and w_s are calculated from the fitted function to the rapidity distribution of secondary particles. We have used Eq. 6.2 to fit the data of rapidity distribution for the most central Au+Au collisions at AGS (2, 4, 8 AGeV), and BRAHMS data at RHIC (62.4 and 200 GeV). The fitting is performed using TMinute class available in ROOT library with χ^2 minimization. The fitting results are shown in FIG. 6.4 along with the fit functions for different energies. Further, these fit functions are used to estimate the baryon stopping at corresponding collision energies.

In the center-of-mass system, the maximum rapidity that an outgoing particle can have after the collision is y_b , which is only possible for full trans-

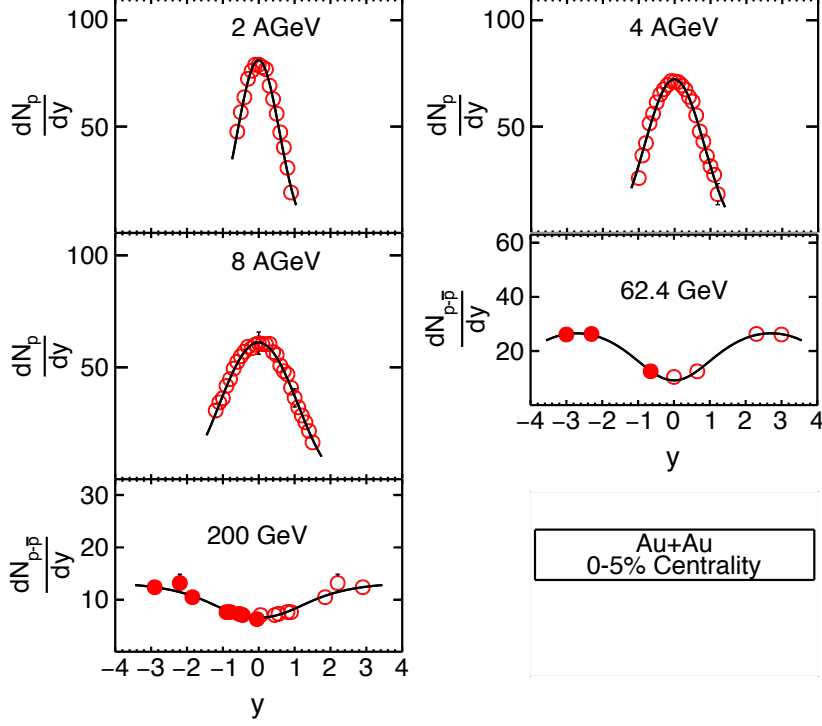


Figure 6.4. The rapidity densities of protons at 2, 4, 8 AGeV (AGS) and net-proton ($N_p - N_{\bar{p}}$) (for RHIC energies) for central Au+Au collisions in the center-of-mass system. Experimental data are from E802 [176], E877 [177], E917 [178], E866 [179] and RHIC experiments [173, 180]. The open circles are experimentally measured data points and the filled circles are the mirror reflections, assuming a symmetry in particle production. Solid lines represent the two source fit function given by Eq. 6.2 [167].

parency. Therefore, by using Eq. 6.2, the fraction of stopped protons in $|y| < 0.5$ (mid-rapidity) at a particular energy can be calculated as,

$$f_{stopped}^{protons} = \frac{\int_{-0.5}^{0.5} \frac{dN}{dy} dy}{\int_{-y_b}^{y_b} \frac{dN}{dy} dy}. \quad (6.3)$$

Hence, the percentage of stopped protons can be estimated as:

$$N_{stopped}^{protons} = f_{stopped}^{protons} \times 100 \%. \quad (6.4)$$

It should be noted here that $\int_{-y_b}^{y_b} \frac{dN}{dy} dy$ gives the total number of partici-

pating protons (N_{part}^B) and for the top central Au+Au collisions, $N_{part}^B \approx 158$. The calculated percentage of stopped protons at these energies are shown in TABLE. 6.1.

$\sqrt{s_{NN}}$ [GeV]	E_{lab} [GeV/nucleon]	$N_{stopped}^{protons}$ [%]
2.35	2	64.22 ± 0.10
3.04	4	52.16 ± 0.15
4.09	8	44.61 ± 0.12
62.4		4.57 ± 0.10
200		2.91 ± 0.0

Table 6.1. Fraction of stopped protons in $|y| < 0.5$ at different energies [175]

Thereafter, by converting the laboratory energy to the center-of-mass energy, a study of stopped protons with $\sqrt{s_{NN}}$ is done. The decreasing behaviour of stopped protons ($N_{stopped}^{proton}$) with $\sqrt{s_{NN}}$ is best described by an exponential function as shown in FIG. 6.5. Our observations go inline with the earlier study [172]. Hence, a parametric form of the stopped protons with $\sqrt{s_{NN}}$ is obtained. This is given by, $N_{stopped}^{protons}[\%] = A \exp(-B \ln(\sqrt{s_{NN}}/s_0))$, where $\sqrt{s_0}$ is taken to be 1 GeV and the obtained fitting parameters are $A = 118.89 \pm 6.18$ and $B = 0.72 \pm 0.05$. Using this parametrized function, we have interpolated the percentage of stopping at RHIC BES energies in $|y| < 0.5$ for $\sqrt{s_{NN}} = 7.7, 11.5, 19.6, 27, 39, 62.4$ and 200 GeV. The values are tabulated in TABLE 6.2.

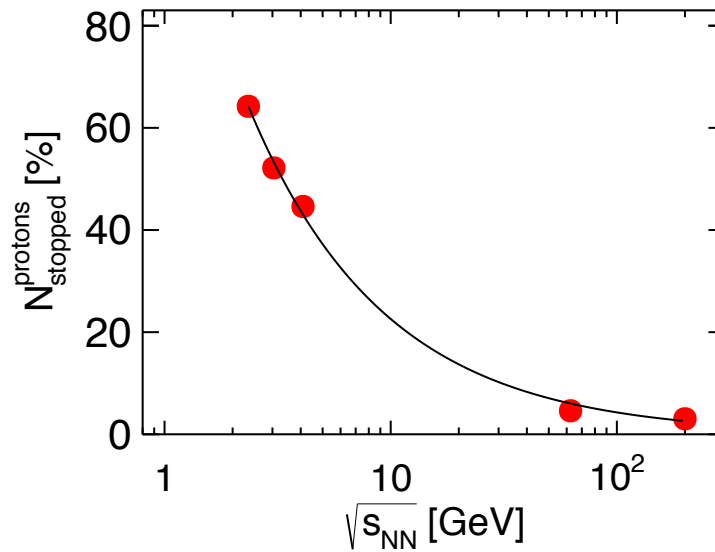


Figure 6.5. Percentage of baryon stopping as a function of $\sqrt{s_{NN}}$, fitted with an exponentially decreasing function with energy [167].

$\sqrt{s_{NN}}$ [GeV]	7.7	11.5	19.6	27	39	62.4	200
$N_{\text{stopped}}^{\text{protons}} [\%]$	27.27	20.43	13.90	11.03	8.46	6.03	2.60
$\text{Err}\{N_{\text{stopped}}^{\text{protons}} [\%]\}$	1.30	1.34	1.25	1.15	1.03	0.86	0.51

Table 6.2. Percentage of stopped protons at different RHIC BES energies in $|y| < 0.5$ acceptance.

Estimation of stopped protons in STAR p_T acceptance:

In the previous section, we have estimated percentage of stopped protons in $|y| < 0.5$ at RHIC BES energies. But, the STAR experiment has measured the protons and antiprotons in $0.4 \text{ GeV}/c < p_T < 0.8 \text{ GeV}/c$ to calculate the higher order cumulants of net-proton distributions [166]. After estimating the number of stopped protons at mid-rapidity, now we calculate the same in the STAR p_T -acceptance. Here we assume that the stopped protons are uniformly distributed over the whole p_T -spectra. To estimate the fraction of the stopped protons in STAR p_T -acceptance we have fitted the protons p_T -spectra at different available BES energies. The fitting is performed with a Levy-Tsallis function, which is given by Eq.11 of Ref. [186] for $\sqrt{s_{NN}} = 9.2, 62.4$ and 200 GeV . Similarly, for $\sqrt{s_{NN}} = 19.6 \text{ GeV}$, the Tsallis distribution function, as given by Eq.6 of Ref. [189] is used. The fitting results of STAR proton data are shown in Figs. 6.6. The ratios in the lower panels of Figs. 6.6 suggest that the used fit functions describe the experimentally measured proton spectra very well for all centre-of-mass energies. We integrate the fitted functions at a particular energy from $p_T = 0.0$ to $p_T = \infty$ and $p_T = 0.4$ to $0.8 \text{ (GeV}/c)$. Thus the total number of protons in the whole p_T range and the number of protons in $0.4 \text{ GeV}/c < p_T < 0.8 \text{ GeV}/c$ are calculated.

The fraction of protons falling in $0.4 \text{ GeV}/c < p_T < 0.8 \text{ GeV}/c$ region is estimated as,

$$f_{p_T}^{\text{protons}} = \frac{N^{\text{protons}}(0.4 < p_T < 0.8)}{N^{\text{protons}}(\text{full } p_T)} \quad (6.5)$$

Hence, the percentage of protons in STAR p_T -acceptance is given by

$$N_{p_T}^{\text{protons}} = f_{p_T}^{\text{protons}} \times 100\% \quad (6.6)$$

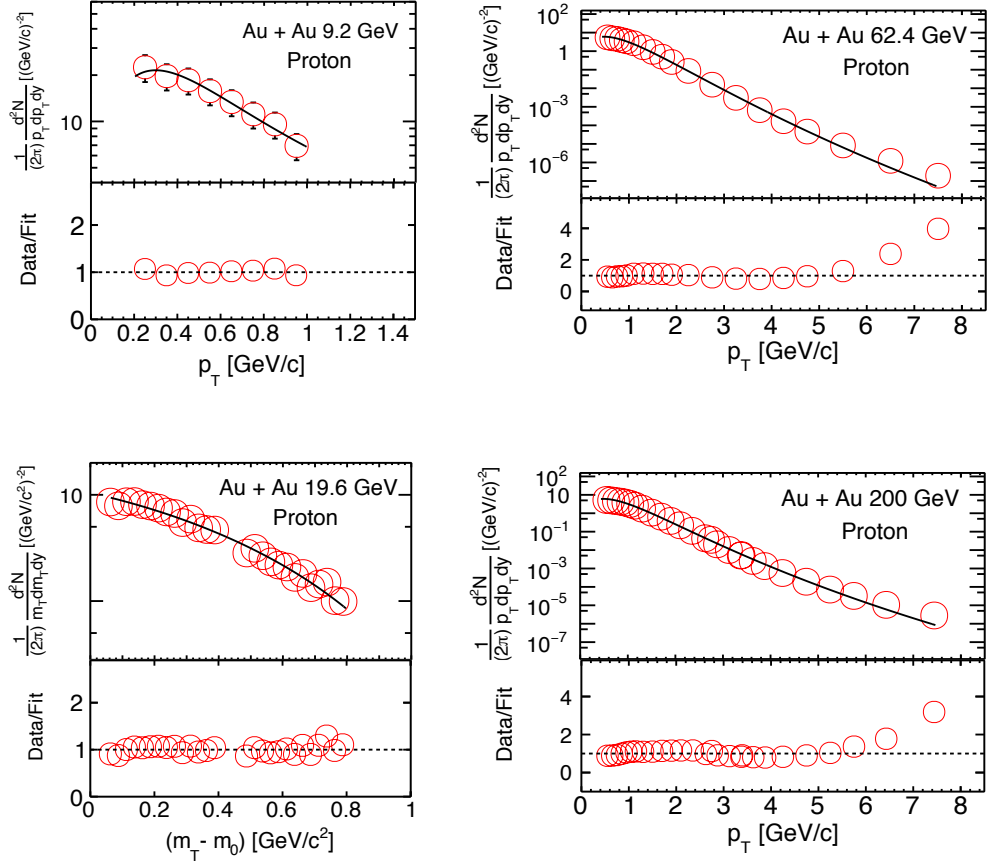


Figure 6.6. Invariant yield of protons at $\sqrt{s_{NN}} = 9.2$ GeV [182], 19.6 GeV [183], 62.4 GeV [184] and 200 GeV [185] for the most central Au + Au collisions. The open circles are the experimental data measured by the STAR Collaboration. The solid lines are the Levy-Tsallis function [186] for $\sqrt{s_{NN}} = 9.2$ and the Tsallis function [189] for $\sqrt{s_{NN}} = 19.6$ GeV. The lower panels show the ratio of data points to their functional values [167].

Using Eqn. 6.6, one can estimate the fraction of stopped protons contributing in STAR p_T -acceptance. To calculate the percentage in the RHIC BES energies, we have parametrized these numbers with $\sqrt{s_{NN}}$ by first order polynomial as shown in FIG. 6.7. Then the contributions at different BES energies are interpolated. The extracted values are tabulated in TABLE 6.3. It is clear from the table that the fraction of stopped protons decrease with collision energy.

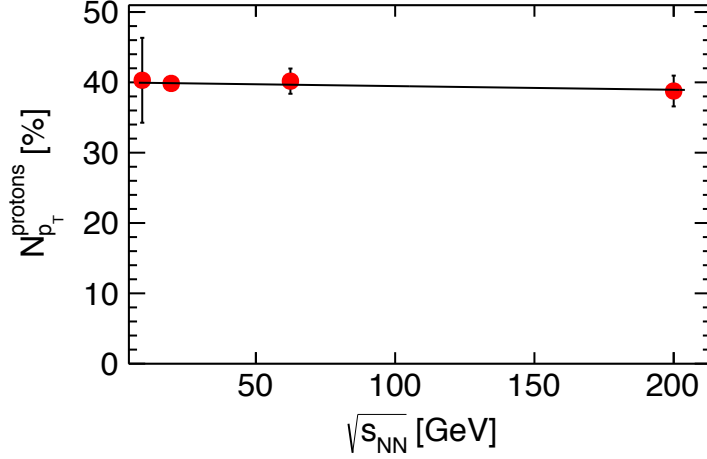


Figure 6.7. Percentage of protons in $0.4 \text{ GeV}/c < p_T < 0.8 \text{ GeV}/c$ as a function of $\sqrt{s_{NN}}$ are being well described by a first order polynomial [167].

$\sqrt{s_{NN}}$ [GeV]	7.7	11.5	19.6	27	39	62.4	200
$N_{pT}^{\text{protons}\%}$	39.95	39.93	39.88	39.84	39.79	39.66	38.94
Err $\{N_{pT}^{\text{protons}\%}\}$	0.60	0.58	0.54	0.52	0.52	0.63	2.11

Table 6.3. Percentage of protons obtained from p_T -spectra at different BES energies in STAR p_T -acceptance.

Contribution of stopped protons in STAR measurements:

In the top central Au+Au collisions, there are around 158 protons participating in each collision. We have already estimated the number of protons in TABLE. 6.1 in $|y| < 0.5$ for full p_T -coverage and in TABLE. 6.3 for $0.4 \text{ GeV}/c < p_T < 0.8 \text{ GeV}/c$. Therefore, one can easily calculate the effect of both to estimate the total stopped protons in STAR acceptance. This is given by

$$N_{\text{stopped}}^{\text{protons}}(\text{STAR}) = 158 \times N_{\text{stopped}}^{\text{protons}\%} \times N_{pT}^{\text{protons}\%}, \quad (6.7)$$

where $N_{\text{stopped}}^{\text{protons}}(\text{STAR})$ is the total contribution of stopped protons in STAR acceptance. In TABLE. 6.4 we enlist the total number of stopped protons at BES energies in STAR acceptance.

Figure. 6.8 shows the energy dependent behaviour of the stopped protons, which is consistent with the fact that stopping is more at lower energies as compared to the higher energies.

$\sqrt{s_{NN}}$ [GeV]	7.7	11.5	19.6	27	39	62.4	200
$N_{\text{stopped}}^{\text{protons}}(\text{STAR})$	17.21	12.89	8.76	6.94	5.32	3.78	1.6
Err $\{N_{\text{stopped}}^{\text{protons}}(\text{STAR})\}$	0.86	0.86	0.80	0.73	0.65	0.54	0.33

Table 6.4. Number of stopped protons at different RHIC BES energies in STAR acceptance.

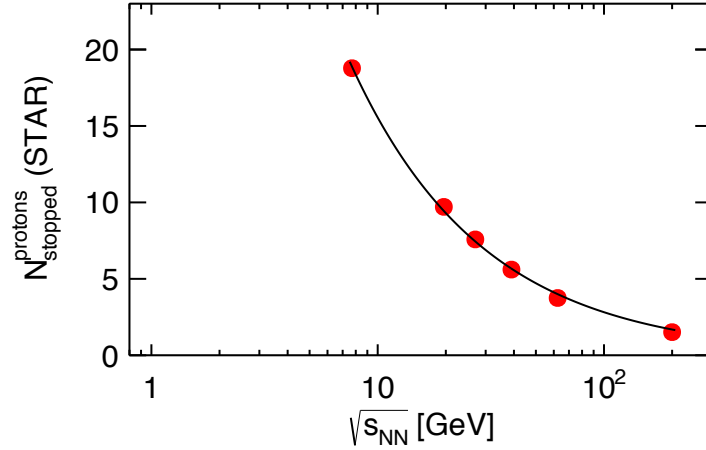


Figure 6.8. Mean number of protons from baryon stopping in STAR acceptance as a function of $\sqrt{s_{NN}}$, showing an exponential decrease with energy [167].

It is interesting to note that after subtracting the stopped protons from the mean of STAR proton distributions [166], the remaining produced protons are consistent with the antiprotons measured by the STAR experiment. This can be seen from TABLE. 6.5. There is a small discrepancy between these two numbers at 7.7 GeV and 11.5 GeV measurements. This may be due to the larger uncertainties in the experimental measurement of protons itself.

(a)	(b)	(c)	(d)	(e)
$\sqrt{s_{NN}}$	$N_{\text{stopped}}^{\text{protons}}(\text{STAR})$	$N_{\text{STAR}}^{\text{protons}}$	Diff.	$N_{\text{STAR}}^{\text{antiprotons}}$
7.7	17.21 ± 0.86	18.92 ± 0.01	1.71 ± 0.86	0.165
11.5	12.89 ± 0.86	15.00 ± 0.01	2.10 ± 0.86	0.49
19.6	9.73 ± 0.80	11.37 ± 0.00	1.63 ± 0.80	1.15
27.0	7.61 ± 0.73	9.39 ± 0.00	1.78 ± 0.73	1.65
39.0	5.78 ± 0.65	8.22 ± 0.00	2.44 ± 0.65	2.38
62.4	3.78 ± 0.54	7.25 ± 0.00	3.47 ± 0.54	3.14
200	1.54 ± 0.33	5.664 ± 0.00	4.12 ± 0.33	4.11

Table 6.5. Column wise: (a) $\sqrt{s_{NN}}$ (in GeV) at which the analysis is performed, (b) Mean number of protons obtained from baryon stopping in STAR acceptance [$N_{\text{stopped}}^{\text{protons}}(\text{STAR})$], (c) Mean number of protons measured by STAR experiment [$N_{\text{STAR}}^{\text{protons}}$] [188], (d) Diff. = [$N_{\text{STAR}}^{\text{protons}} - N_{\text{stopped}}^{\text{protons}}(\text{STAR})$], and (e) Mean number of antiprotons measured by STAR experiment [$N_{\text{STAR}}^{\text{antiprotons}}$].

6.1.2 Experimental Implications

The discussed methodology would lead to the estimation of the number of stopped protons that could improve the understanding of dynamical fluctuations. Particularly, the $\kappa\sigma^2$ variable of the produced protons *only*, will be useful to study the criticality in the QCD phase diagram. As, it is not possible to tag a proton from stopping or production in experimental data, the correction for the stopped protons to the net-proton multiplicity distribution can't be applied to the experimental measurement. The exact distribution of stopped protons on an event-by-event basis is not known and hence, it is difficult to subtract the contribution of stopped protons from the inclusive proton distribution, which needs further investigations. Therefore, it is suggested that, while quoting the fluctuation results from net-proton multiplicity distribution, a systematic uncertainty may be added by using the Monte Carlo simulations and the results of this study to quantify the effect of stopping on the fluctuations in their respective acceptance. This proposed analysis bears values in the low energy BES program of RHIC, where a search for critical point and the associated criticality becomes prudently viable.

6.1.3 Summary

In the present work, we use the data of net-proton rapidity distributions for the most central Au+Au collisions measured by different experiments. Further, we use a two source function [170], to analyze the net-proton distributions and calculate the percentage of stopped protons at different center-of-mass energies. Then the percentage of stopped protons is interpolated at RHIC BES energies. Afterwards, using invariant transverse momentum spectrum we estimate the fraction of the number of protons contributing in STAR acceptance. Finally, using these two numbers, we estimate the contribution of stopped protons in $|y| < 0.5$ and transverse momentum between 0.4 GeV/c and 0.8 GeV/c, which is used to measure the protons and antiprotons by STAR experiment for net-proton fluctuation studies [166]. The critical point of QCD phase diagram is expected to show large dynamical fluctuations in the produced conserved

charges. Therefore, it will be exciting to see these results after removing the contribution of stopped protons, which have significant contributions, particularly at lower collision energies. My colleague P. Garg et al. has taken forward to the current work, where they have subtracted the stopping contribution from the inclusive proton distribution [168, 169] by a Monte Carlo method. After removing the stopping contribution from the inclusive proton distribution, the cumulant ratios, C_3/C_2 and C_4/C_2 , of the net-proton multiplicity distribution have been studied which shows non-monotonic behavior around $\sqrt{s_{NN}} = 19.6$ GeV. This may indicate the presence of a critical point or a phase-transition in high-energy heavy-ion collisions and the behavior was not solely due to baryon stopping. This is the only attempt has been made to separate the stopped and produced proton fluctuations from the net-proton fluctuations

6.2 Inferring freeze-out properties of hadrons by Tsallis non-extensive statistics

¹ The Tsallis formalism was introduced three decades ago [82]. It is a non-extensive generalization of the statistical mechanics and has been very successful in describing very different physical systems in terms of statistical approach. The standard statistical mechanics is based on the Boltzmann-Gibbs (BG) entropy, $S_{BG} = -k \sum_{i=1}^W p_i \log p_i$, where $\sum_{i=1}^W p_i = 1$ and W is the number of microscopic states. This extremely powerful theory is one of the pillars of contemporary physics. This theory has exhibited many successes in describing different phenomena through the thermally equilibrated distribution, $p_i \propto e^{-\beta E_i}$, E_i is the energy of corresponding microstate. For non-ergodic systems, which is quite frequently the case of the so-called complex systems, there is no general reason for legitimately using the BG theory. In that case, It is frequently referred to use of non-extensive statistical mechanics, because the total energy of such system is not proportional to the total number of elements present in

¹Adv. High Energy Phys. 2016 (2016) 4149352, **Dhananjaya Thakur**, Sushanta Tripathy, Prakhar Garg, Raghunath Sahoo, Jean Cleymans.

the system. This theory is based on the entropy:

$$S_q = k \frac{1 - \sum_i p_i^q}{q - 1} \quad (6.8)$$

Where, the total Tsallis entropy (S_q) of two probabilistically independent systems “A” and “B” ($p_{ij}^{A+B} = p_i^A p_j^B$) is not equal to the sum of the entropies of the subsystems, but is given by;

$$\frac{S_q(A+B)}{k} = \frac{S_q(A)}{k} + \frac{S_q(B)}{k} + (1-q) \frac{S_q(A)}{k} \frac{S_q(B)}{k} \quad (6.9)$$

It is in contrast with S_{BG} which is additive, the entropy, S_q , is non-additive. This non-additivity enables it to be non-extensive. The non-extensive statistics converge to BG statistics when $q=1$.

The two parameter Tsallis distribution based on the entropy S_q is given by [190],

$$f(X) = C \cdot \left(1 + \frac{X}{mT}\right)^{-m} \quad (6.10)$$

Where the scale parameter “T” is identified in thermodynamical applications with the usual temperature although such argument is not solid. The power index $m = 1/(q - 1)$. The non-extensive parameter “q” is related to temperature fluctuation [191]. When $q \rightarrow 1$, Eq. 6.10 converge to usual BG distribution $f(X) = C \exp(-X/T)$.

It is now well-documented that the transverse momentum distribution of various particles at high energy and in a very broad range of p_T is well described by the Tsallis distribution [192–198]. This observation is usually interpreted in terms of the statistical model of particle production, employing the Tsallis non-extensive statistics. The corresponding statistical freeze-out parameters of hadronic species at the time of their freeze-out can be obtained from the analysis of their respective transverse momentum distributions. Different forms of the invariant yields using Tsallis distribution are available in the literature [199–201]. In the present work we have used all of these forms to study the system size, mass and energy dependence of the temperature (T), chemical potential (μ), radial flow (β), volume (V), and non-extensive parameter (q).

6.2.1 Different forms of Tsallis distribution to describe the p_T spectra

In this section, we have discussed transverse momentum spectra of identified particles (π^+ , K^+ , p and their antiparticle) produced in RHIC and LHC experiments using different forms of Tsallis non-extensive statistics.

Non-extensive statistics without radial flow:

The Tsallis distribution function at mid-rapidity to describe the transverse momentum distribution, with finite chemical potential and without radial flow [200] is given by,

$$\frac{1}{p_T} \frac{d^2 N}{dp_T dy} \Big|_{y=0} = \frac{gV m_T}{(2\pi)^2} \left[1 + (q-1) \frac{m_T - \mu}{T} \right]^{-\frac{q}{q-1}} \quad (6.11)$$

where, m_T is the transverse mass of a particle given by $\sqrt{p_T^2 + m^2}$, g is the degeneracy and μ is the chemical potential of the system. In view of higher center-of-mass energies, where $\mu \simeq 0$, the transverse momentum distribution function [201] becomes:

$$\frac{1}{p_T} \frac{d^2 N}{dp_T dy} \Big|_{y=0} = \frac{gV m_T}{(2\pi)^2} \left[1 + (q-1) \frac{m_T}{T} \right]^{-\frac{q}{q-1}}. \quad (6.12)$$

As is well-known the Tsallis distribution introduces a new parameter “ q ” which for transverse momentum spectra is always close to 1. Typical values for the parameter “ q ” obtained from fits to the transverse momentum distribution are in the range 1.0 to 1.2 [210]. It is to be noted that the expressions Eq. 6.11 and Eq. 6.12 are thermodynamically consistent. This form of Tsallis distribution function has an extra power, q , to make the function thermodynamically consistent. As $1.0 \leq q \leq 1.2$, this extra power does not make any quantitative difference for hadronic and nuclear collisions.

Non-extensive statistics with radial flow:

The value of the non-extensive parameter q for high energy collisions is $1 \leq q \leq 1.2$ [210]. To study the order of deviation of the p_T -spectra from a equilibrium Boltzmann distribution, the Tsallis distribution function has been expanded in a Taylor series in view of $(q - 1)$ being very small, after successful inclusion of radial flow in a relativistic scenario. The details of the method are described in Ref. [199]. The functional form of the distribution up to first order in $(q - 1)$ is given by

$$\begin{aligned} \frac{1}{2\pi p_T} \frac{dN}{dp_T dy} &= \frac{gV}{(2\pi)^3} \\ &\left\{ 2T[rI_0(s)K_1(r) - sI_1(s)K_0(r)] - \right. \\ &(q-1)Tr^2I_0(s)[K_0(r) + K_2(r)] + \\ &4(q-1)TrsI_1(s)K_1(r) - (q-1)Ts^2K_0(r) \\ &[I_0(s) + I_2(s)] + \frac{(q-1)}{4}Tr^3I_0(s) \\ &[K_3(r) + 3K_1(r)] - \\ &\frac{3(q-1)}{2}Tr^2s[K_2(r) + K_0(r)]I_1(s) + \\ &\frac{3(q-1)}{2}Ts^2r[I_0(s) + I_2(s)]K_1(r) \\ &\left. - \frac{(q-1)}{4}Ts^3[I_3(s) + 3I_1(s)]K_0(r) \right\} \end{aligned} \quad (6.13)$$

where, $r \equiv \frac{\gamma m_T}{T}$, $s \equiv \frac{\gamma \beta p_T}{T}$. $I_n(s)$ and $K_n(r)$ are the modified Bessel functions of the first and second kind. There are four parameters involved namely V , T , β and q ; where V is the volume, T is the Tsallis temperature, β is the radial flow velocity and q is the Tsallis non-extensive parameter. We use Eq. 6.13 to fit the particle spectra of identified particles in heavy ion collisions to study the radial flow parameter.

6.2.2 Results and Discussion

It is expected that the number of binary collisions in a system with smaller number of participant nucleons is quite low. Hence, the probability of mu-

tual interaction (resulting in momentum transfer) between the system quanta: partons or hadrons, becomes less for the systems with small value of participating nucleons. This makes the system to stay away from a possible thermal equilibrium. On the other hand, an appreciable increment in the number of binary collisions is observed in a system possessing a large number of participant nucleons and consequently the system can reach quickly to its thermal equilibrium or in the close vicinity of it. It has been shown in Ref. [202], that the non-extensivity parameter (q) is close to one in central Au+Au collisions and increases towards peripheral collisions. A higher value of q reflects that the system being away from thermal equilibrium. These results suggest that the degree of non-equilibrium is higher in peripheral collisions. Such systems are best described by Tsallis distributions, for example the most peripheral A+A and p+p systems. Keeping all the parameters free, we perform the fitting of invariant p_T spectra for $p_T < 3$ GeV/c around mid rapidity at $\sqrt{s_{NN}} = 200$ GeV and $\sqrt{s_{NN}} = 2.76$ TeV with Eqns. 6.12, 6.11 and 6.13 independently for different particles like π^+ , K^+ , p and their antiparticle. The analysis has been done for most peripheral Pb+Pb and Au+Au collisions as well as $p+p$ collisions at the mentioned center-of-mass energies. In the following sections, we have discussed the present analysis in three different sections, depending on which kind of Tsallis distribution is used to describe the p_T spectra.

Tsallis Distribution (V, T, q):

Eq. 6.12 is used to analyze invariant p_T spectra of identified particles (π^+ , K^+ , p and their antiparticles) for most peripheral Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV and most peripheral Pb+Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV. The analysis has been extended to $p + p$ collisions at both energies to study the system size dependence. The fitting results of p_T spectra of identified particles for most peripheral Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV and Pb+Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV is shown in Fig 6.9. The lower panel of the same figure shows the fitting result of invariant p_T spectra for $p + p$ collisions at $\sqrt{s_{NN}} = 0.2$ and 2.76 TeV respectively. The fitting is performed up to the maximum p_T of 3 GeV/c for A+A collisions and 2.5 GeV/c for $p + p$ collisions although

the K^+ p_T spectrum in Au+Au collision is fitted only up to 2.0 GeV/c due to unavailability of data [203].

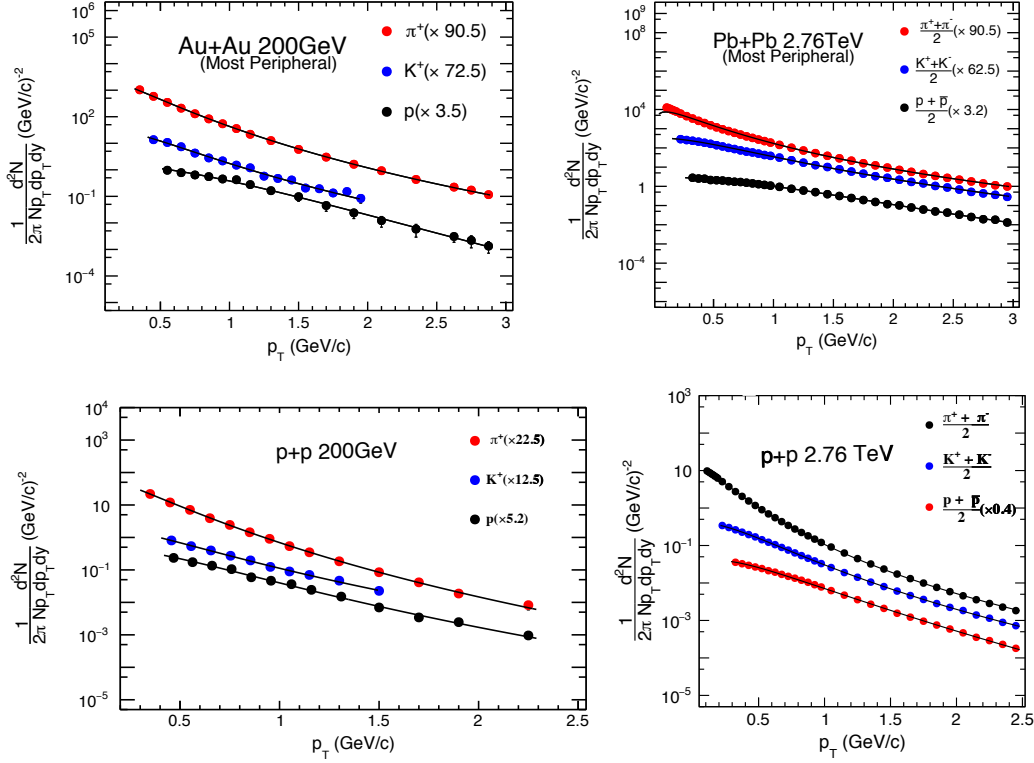


Figure 6.9. (color online) Fitting of invariant p_T spectra with Tsallis distribution using Eq. 6.12 for π^+ [203], K^+ [203] and p [203] in most peripheral Au+Au collisions at $\sqrt{s_{NN}}=200$ GeV and Pb+Pb collisions at $\sqrt{s_{NN}}=2.76$ TeV. The fitting is repeated for p+p collisions at the respective energies [204, 205] and are presented at the lower panels. Symbols represent the data points and line is the fit function [189].

It can be clearly seen from the figure that the fittings results of Tsallis function with $\mu = 0$ seem to be a good description of the peripheral heavy-ion and p+p collisions. This is due to the fact that in both the cases, due to less particle multiplicity in the final state and hence less number of binary collisions, the formed system stays away from a thermal equilibrium. Therefore, such kind of systems are better described by Tsallis non-extensive statistics. The χ^2/ndf obtained by minimization in TMinuit are shown in Fig. 6.10. The χ^2/ndf values are around unity for all the collision systems as well as all the particle species.

Please note that we have considered the fitting results for which the fittings are conversed.

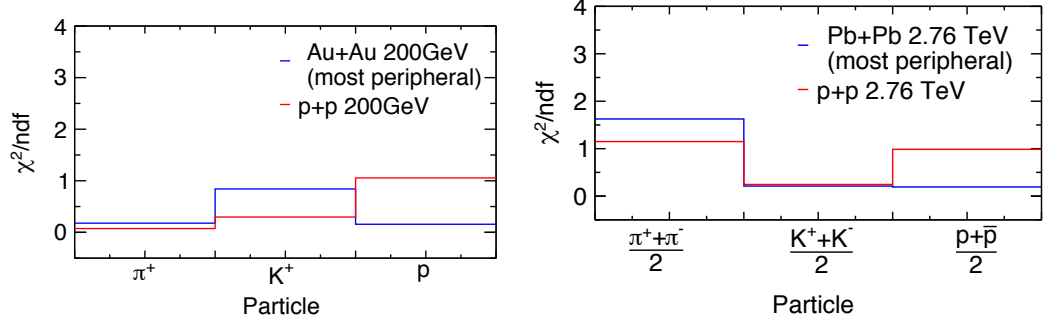


Figure 6.10. (color online) **Left:** χ^2/ndf values are shown for most peripheral Au+Au and $p + p$ collisions at $\sqrt{s_{NN}} = 200$ GeV using Eq. 6.12 as a fit function. **Right:** χ^2/ndf values are shown for most peripheral Pb+Pb and $p + p$ collisions at $\sqrt{s_{NN}} = 2.76$ TeV using Eq. 6.12 as a fit function [189].

A systematic study of the extracted parameters from the fitting results: volume (V), temperature (T) and Tsallis non-extensive parameter (q) are studied as a function of mass of the particle. The values of extracted parameters are summarized in table. 6.6. Using the volume parameter (V), we have calculated the radius of the fireball at freeze-out considering it as spherically symmetry and plotted as a function of the mass of the identified particles. Figure 6.11 shows the mass dependence of the thermodynamic parameters at $\sqrt{s_{NN}} = 200$ GeV and $\sqrt{s_{NN}} = 2.76$ TeV. We have compared the parameters obtained for peripheral heavy-ion collisions with that of $p + p$ collisions at the same centre-of-mass energies to understand the thermodynamic properties of the produced systems. Basically, to know about the thermodynamical distinction between the systems formed in A+A and p+p collisions.

It is found that the volume (radius of the fireball) parameter decreases with increase in particle mass. It indicates that different particles have different freeze-out surfaces depending on their mass. This is observed both for p+p and A+A collisions and thus indicates a mass dependent differential freeze-out scenario in high-energy collisions. In view of the above freeze-out picture,

Au+Au 200 GeV (Peripheral)				
Particle	χ^2/ndf	$V (fm)^3$	$T (GeV)$	q
π^+	0.178	2242.35 ± 18.23	0.093 ± 0.003	1.113 ± 0.004
K^+	0.842	223.358 ± 0.010	0.085 ± 0.011	1.120 ± 0.002
p	0.157	45.62 ± 2.45	0.205 ± 0.012	1.025 ± 0.029
$p + p$ 200 GeV				
π^+	0.073	5293.1 ± 23.3	0.088 ± 0.004	1.103 ± 0.005
K^+	0.297	2443.7 ± 33.7	0.066 ± 0.002	1.161 ± 0.009
p	1.055	360.5 ± 9.6	0.113 ± 0.004	1.070 ± 0.000
Pb+Pb 2.76 TeV (Peripheral)				
Particle	χ^2/ndf	$V (fm)^3$	$T (GeV)$	q
$\frac{\pi^+ + \pi^-}{2}$	1.626	6134.30 ± 12.61	0.082 ± 0.001	1.156 ± 0.002
$\frac{K^+ + K^-}{2}$	0.211	629.69 ± 14.80	0.133 ± 0.003	1.120 ± 0.004
$\frac{p + \bar{p}}{2}$	0.193	39.623 ± 1.052	0.238 ± 0.012	1.052 ± 0.009
$p + p$ 2.76 TeV				
$\frac{\pi^+ + \pi^-}{2}$	0.985	1102.46 ± 6.82	0.070 ± 0.001	1.163 ± 0.001
$\frac{K^+ + K^-}{2}$	0.094	127.13 ± 1.33	0.096 ± 0.005	1.144 ± 0.005
$\frac{p + \bar{p}}{2}$	0.006	291.39 ± 10.62	0.069 ± 0.003	1.133 ± 0.002

Table 6.6. χ^2/ndf and different extracted parameters from Tsallis distribution fit(Eq. 6.12) to the p_T spectra of (a) π^+ , K^+ and p for most peripheral Au+Au collisions and $p + p$ collisions at $\sqrt{s_{NN}} = 200$ GeV; (b) $\frac{\pi^+ + \pi^-}{2}$, $\frac{K^+ + K^-}{2}$ and $\frac{p + \bar{p}}{2}$ for most peripheral Pb+Pb collisions and $\frac{\pi^+ + \pi^-}{2}$, $\frac{K^+ + K^-}{2}$ and $\frac{p + \bar{p}}{2}$ for $p + p$ collisions at $\sqrt{s_{NN}} = 2.76$ TeV.

considering T as the freeze-out temperature, we observe from Fig. 6.11 that the freeze-out temperature slightly increases with increase of particle mass. This observation goes inline with the earlier findings of Ref. [206], which uses a slightly different approach. It clearly indicates that the heavier particles have higher freeze-out temperatures as compared to lighter particles. This observation goes inline with an intuitive expectation of mass dependent particle freeze-out or differential freeze-out. In literature, one can find various freeze-out scenarios like, single freeze-out [207], strange and non-strange particles having two different freeze-outs [208, 209] etc. However, our findings from the analysis of high-energy particle spectra with non-extensive statistics reveals a consistent differential freeze-out scenario with particles and their counter parts, the anti-particles freezing out at the same time (characterized by freeze-out temperature, freeze-out volume) from the produced fireballs. The non-extensive measure i.e., the q -parameter obtained from our studies is consistent with its standard value, $1 < q < 1.2$, both for $p + p$ and peripheral A+A

collisions. This goes inline with the expectations of the q -values in high-energy collisions [210]. Fig. 6.11 indicates a similar mass ordering for $p + p$ and A+A systems, indicating that the system formed in most peripheral A+A and $p + p$ collisions are of similar thermodynamic nature. However, it should be noted that the obtained parameters seem to be unphysical *i.e.* volume or the radius in $p + p$ collisions seem to be higher than the peripheral A+A collisions at the same energy. This problem is observed to be circumvented, when one adds the radial flow to the distribution 6.2.2.

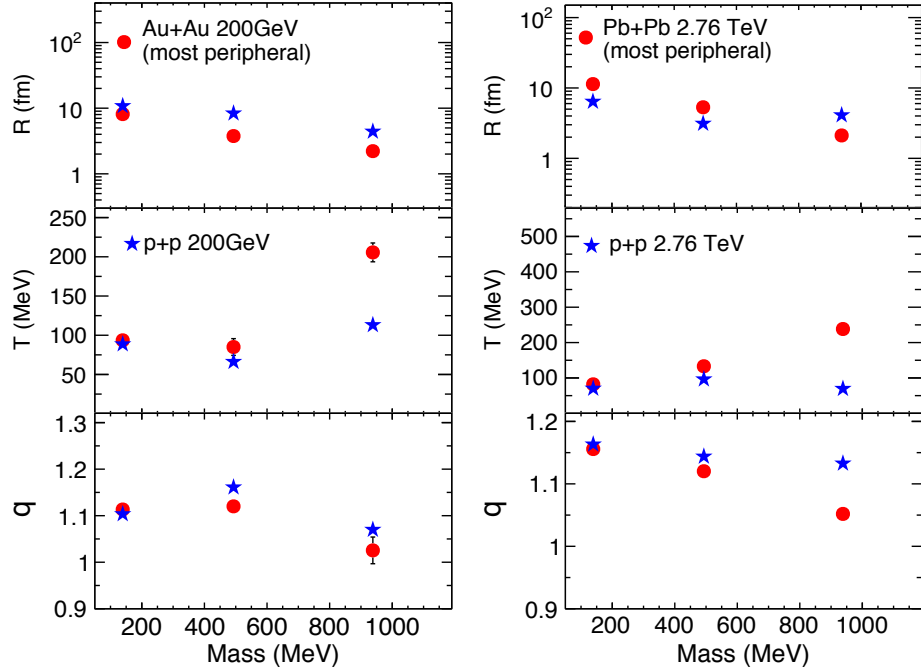


Figure 6.11. (color online) Mass dependence of the thermodynamic parameters using Eq. 6.12 for most peripheral Au+Au and Pb+Pb as well as $p + p$ collisions at $\sqrt{s_{NN}} = 200$ GeV and $\sqrt{s_{NN}} = 2.76$ TeV respectively [189].

Tsallis Distribution (V , T , q , μ):

To know about the energy, system size and mass dependence of chemical potential, we have performed the fitting of invariant p_T spectra of identified particles using Eq. 6.11 which contains an additional parameter as chemical potential (μ). The same fitting procedure is used to fit Au+Au most peripheral collisions at $\sqrt{s_{NN}} = 200$ GeV for identified particles as well as their antiparticles. As

LHC operates at almost zero chemical potential, we have not done the analysis for $\sqrt{s_{NN}} = 2.76$ TeV. The Tsallis form of invariant yields including μ is used in Fig. 8.1 (in appendix section) to fit the p_T spectra of identified particles. It fits up to $p_T \sim 3$ GeV/c for most peripheral collisions. The goodness of fit can be seen from χ^2/ndf values shown in figure 6.12.

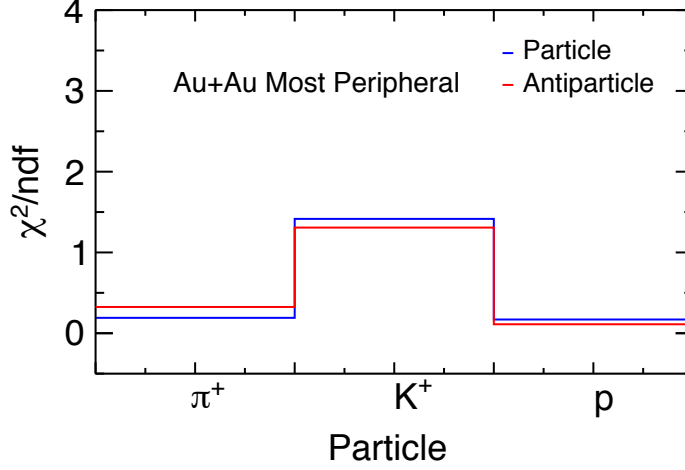


Figure 6.12. (color online) χ^2/ndf values are shown for most peripheral Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV using Eq. 6.11 as a fit function [189].

The mass dependence of extracted parameters are shown in the figure 6.13. The values of the parameters are tabulated in Table. 8.1 of the appendix. In figure 6.13, one can clearly see that all the parameters follow the same mass dependent trend as is discussed in the previous case. As we have already discussed a detailed of mass dependence of the extracted parameters except the chemical potential (μ), in this section we have only discussed the behavior of chemical potential (μ) with mass. It is to be mentioned here that, the chemical potential is extracted from the invariant yields at the thermal freeze out, where all the elastic processes cease. Hence, the obtained chemical potential here is called thermal chemical potential. At this stage one can introduce chemical potentials for all particle species (μ_i). Following Ref. [211], the relationship between chemical potential at kinetic freeze-out and chemical potential

at chemical freeze-out is,

$$\mu_{TH} = \mu_{CH} \frac{T_{TH}}{T_{CH}} + m(1 - \frac{T_{TH}}{T_{CH}}) \quad (6.14)$$

where (T_{CH}, T_{TH}) and (μ_{CH}, μ_{TH}) are temperatures and chemical potentials at chemical and thermal freeze-out respectively. Eq.6.14 clearly shows a mass dependency of thermal chemical potential. The extracted parameters shown in Fig. 6.13 show a consistent picture for particles and antiparticles in case of most peripheral collisions. It is evident from Fig. 6.13 that the μ -parameter increases with particle mass. It shows that particles and antiparticles have same freeze-out conditions. It is worth mentioning here that the the parameters T and μ extracted from identified particle spectra using Eqn.6.11 are related by [212],

$$T = T_0 + (q - 1)\mu, \quad (6.15)$$

where $T = T_0$ for $\mu = 0$. Our extracted parameters using Eqn. 6.11 (i.e. T, μ and q) and 6.12 (i.e. $T \equiv T_0$) seem to obey the above relation.

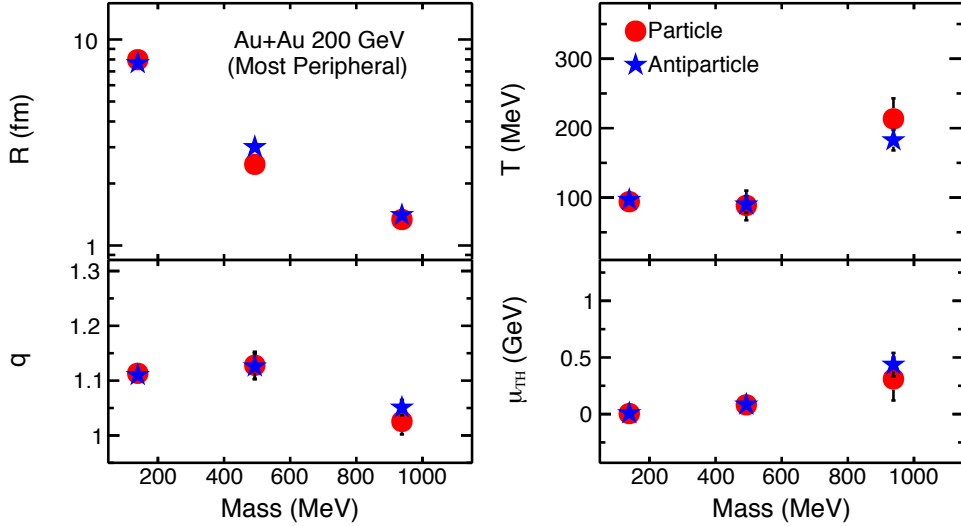


Figure 6.13. (color online) Mass dependence of extracted thermodynamic parameters using Eq. 6.11 for different particles and their corresponding antiparticles for most peripheral Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV [189].

Tsallis Distribution (V , T , q , β):

Finally, the invariant p_T spectra of identified particles is fitted with Eq. 6.13 for most peripheral collisions of Au+Au at $\sqrt{s_{NN}} = 200$ GeV and Pb+Pb at $\sqrt{s_{NN}} = 2.76$ TeV. Besides, the fitting of identified particles for $p + p$ collisions is done for same energies. The fitting results for Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV and the results for Pb+Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV are shown in Figs. 8.2 and 8.3, respectively. Also, the fitting results for $p + p$ collisions at $\sqrt{s_{NN}} = 200$ GeV and $\sqrt{s_{NN}} = 2.76$ TeV are shown in Figs. 8.4 and 8.5, respectively in the appendix section.

The fitting is performed up to $p_T \sim 3$ GeV/c in A+A collisions and $p_T \sim 2.5$ GeV/c in $p + p$ collisions, only a slight deviation at higher p_T is observed in pion spectra. The values of various parameters obtained from the fits are provided in table. 6.3. It is observed from the values of χ^2/ndf (Table. 8.2 of appendix section) that the performance of the present approach is quite satisfactory, except in case of pions, which can be seen from Fig. 6.14.

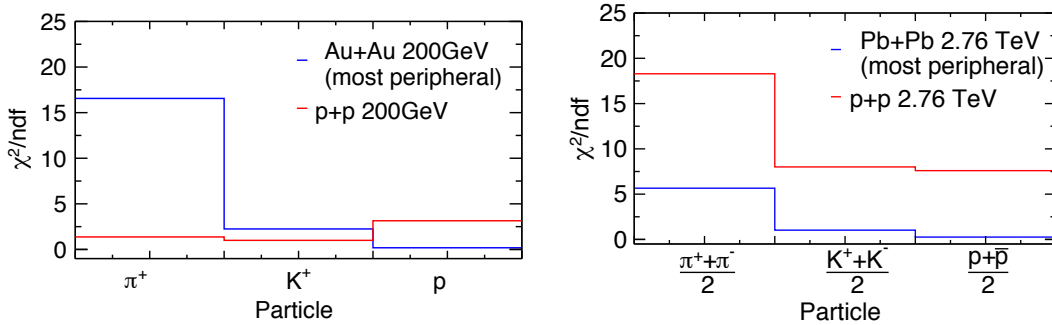


Figure 6.14. (color online) **Left:** χ^2/ndf values are shown for most peripheral Au+Au collision and $p + p$ collisions at $\sqrt{s_{NN}} = 200$ GeV using Eq. 6.13 as a fit function. **Right:** χ^2/ndf values are shown for most peripheral Pb+Pb collisions and $p + p$ collisions at $\sqrt{s_{NN}} = 2.76$ TeV using Eq. 6.13 as a fit function [189].

Then we make a mass dependent study of these parameters. Figs. 6.15 and 6.16 represent the behaviour of the extracted parameters. The parameters like volume, temperature and q show a similar mass dependent behaviour as that of the parameters obtained from the fitting using Eq. 6.12 and Eq. 6.11. Here, through Eq. 6.13, we have introduced an additional radial flow parameter

(β). Figs. 6.15 and 6.16 show the decrease of radial flow with increase of particle mass, which is a signature of hydrodynamic evolution of the system created in high energy collisions. The change of temperature parameter with the use of different forms of Tsallis distribution could be observed in Ref. [213]. In our analysis we have also observed not only the temperature but also the other parameters are changing with the use of different forms of Tsallis distributions. For example, it is observed that with the inclusion of radial flow, the value of the q -parameter becomes less, as compared to that observed in the other forms of Tsallis distribution, while describing the p_T -spectra. This may hint that the non-extensivity is shared by the dynamics of the system [214–216]. In other words the degree of collectivity and the non-extensivity are correlated.

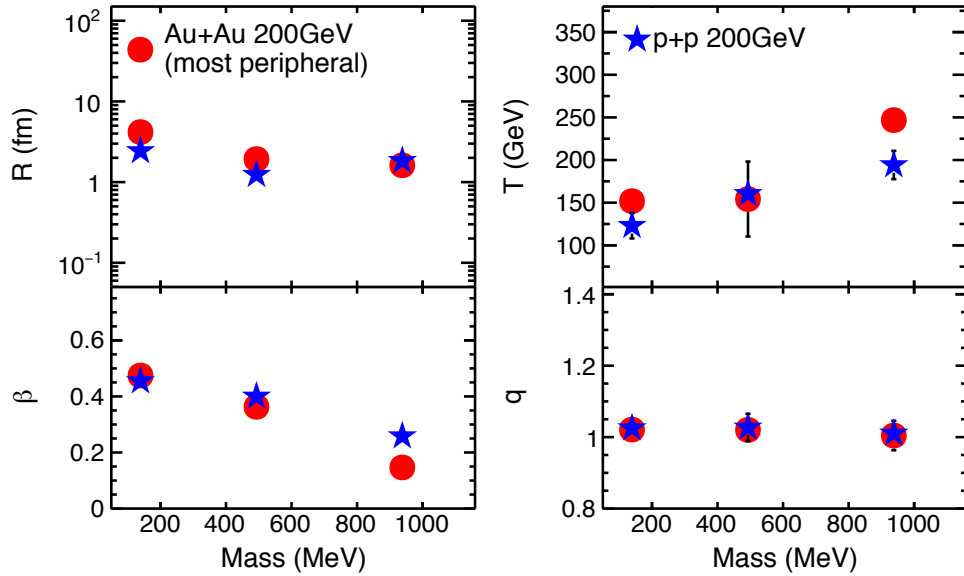


Figure 6.15. (color online) Mass dependence of extracted thermodynamic parameters of Tsallis distribution including radial flow using Eq. 6.13 for most peripheral Au+Au collisions and $p + p$ collisions at $\sqrt{s_{NN}} = 200$ GeV [189].

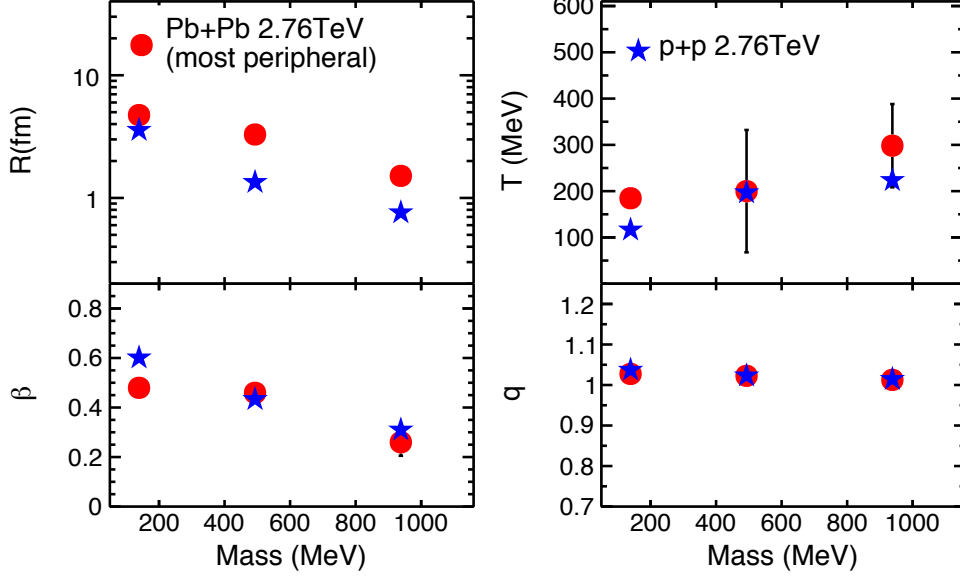


Figure 6.16. (color online) Mass dependence of extracted thermodynamic parameters of Tsallis distribution including radial flow using Eq. 6.13 for most peripheral Pb+Pb collisions and $p + p$ collisions at $\sqrt{s_{NN}} = 2.76$ TeV [189].

6.2.3 Summary

We present a systematic study of the parameters extracted from transverse momentum spectra of produced identified particles in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV and Pb+Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV. Further, the same analysis is done for $p + p$ collisions at both, RHIC and LHC energies. In the present work different forms of invariant yields using Tsallis distribution are used. Parameters obtained from three different forms in most peripheral Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV and in most peripheral Pb+Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV follow a similar trend. Similar behaviour has been observed in $p + p$ collisions for both the energies. The chemical potential plays an important role in particle production mechanism. We observe that the particles produced at early stage have higher thermal chemical potential as compared to particles produced at the later stage. The radial flow extracted from the particle spectra of peripheral A+A collisions is similar to $p + p$ collisions at the same center-of-mass energy. In the discussed low- p_T region, the radial flow decreases with increasing mass,

which goes in line with hydrodynamic description of the evolution of a fireball created in high-energy collisions. Therefore, the present analysis gives a systematic information of hydrodynamical and thermodynamical evolution of the system, while making a direct comparison with hadronic and peripheral nuclear collisions. We observe a mass dependent differential freeze-out scenario in high-energy hadronic and nuclear collisions, which is also supported by similar observations by other works [\[218\]](#).

Chapter 7

Summary and Outlook

The work discussed in this PhD thesis has been carried out at Indian institute of Technology (IIT), Indore within the ALICE Collaboration at CERN LHC. The PhD project focused on three different aspects of the high energy collisions which comprises experimental data analysis as well as phenomenological study to understand the medium formation in heavy-ion and proton-proton collisions.

- J/ψ is thought to be a unique candidate to probe the initial state of the collisions, as it forms very early in the collision and hence experience the whole evolution of the system. Particularly, J/ψ is a accepted probe for the deconfined medium in heavy-ion collisions. To draw a solid conclusion about the medium formation in heavy-ion collision out of the observable one must understand the pp collisions, as it uses as baseline measurement for the study. Furthermore, the creation and decay/annihilation of J/ψ in hadronic collisions itself is a challenging problem in QCD. The majority part of the project for this thesis work is the multiplicity dependence study of J/ψ production and decay via $\mu^+\mu^-$ channel in pp collisions using the data collected by ALICE at the LHC. In the presented work, we have tried to study the production mechanism of J/ψ in different multiplicity environment. Where, a multiplicity estimator has been developed to measure the charged-particle multiplicity using SPD tracklets at the mid-rapidity. This study is very important keeping in mind the recently observed QGP like behavior in high multiplicity pp collisions and also to get the information about the event structure in terms of multipartonic interaction (MPI) scenario. Model study of the observed pictures have been done using PYTHIA8 model which incorporate MPI as the initial

state and color reconnection (CR) as the final state effect.

- Secondly, we have tried to understand the location of the critical point which is predicted to exist at finite baryon chemical potential (μ_B) and temperature (T) in the QCD phase diagram through baryon stopping. The net-proton fluctuation results of the STAR (Solenoidal Tracker At RHIC) experiment from the beam energy scan (BES) program at the BNL Relativistic Heavy Ion Collider (RHIC) have drawn much attention to exploring the QCD critical point and the nature of deconfinement phase transition. There has been much speculation that the non monotonic behavior of $\kappa\sigma^2$ of the produced protons around $\sqrt{s_{NN}}=19.6$ GeV in the STAR results may be due to the existence of a QCD critical point. However, the experimentally measured proton distributions contain protons from heavy resonance decays, from baryon stopping, and from direct production processes. In the work presented in this thesis, we have developed and demonstrate a method to estimate the number of stopped protons at RHIC BES energies for central 0-5 % Au+Au collisions within STAR acceptance and discuss its implications on the net-proton fluctuation results.
- Lastly, the thermodynamics of the freeze out stages (hadronic phase) has been studied using Tsallis non-extensive thermodynamics. Where, we have analyzed transverse momentum spectra of different identified particles using Tsallis non-extensive statistics for pp collisions and most peripheral Au–Au collisions and the mass dependence of thermodynamical quantities have been studied.

Several results have been obtained by the end of the PhD project and major finding of the thesis are listed below,

- **J/ ψ yield vs. multiplicity:** Forward-rapidity quarkonia versus mid-rapidity charged-particle multiplicity is showing almost a linear increase, irrespective of collision energy, quark content and mass of the particle. While, a faster than linear trend is observed for J/ ψ without rapidity

gap. The results hinting for auto-correlation and/or jet-bias for mid rapidity J/ψ vs. mid rapidity charged-particle multiplicity study. Also, the linear scaling of light-flavor particle with multiplicity revealing that event activity affecting same way to the light flavor as well as heavy-flavor particles.

- **$J/\psi\langle p_T \rangle$ vs. multiplicity:** The $\langle p_T \rangle$ of J/ψ is increasing with increasing multiplicity with a little saturation towards higher multiplicity. The observation hinting for collectivity at high multiplicity where as another possible explanation from the MPI prospect is that the high multiplicity events are produced by MPIs and incoherent superposition of such interactions would lead to constant $\langle p_T \rangle$ at high multiplicity. The relative $\langle p_T \rangle$ of J/ψ as a function of multiplicity is found to be independent of center-of-mass energy which further pointing, the event activity associated with the production of J/ψ is independent of $\sqrt{s}$, rather dependent on multiplicity. Model comparisons needed to give a clear picture regarding associated phenomena like MPI, color connection, flow like effect etc. When we compare our results with that of p–Pb collisions, the trend of pp is found to be similar as p–Pb up to $N_{ch} \approx 1.2$, and beyond p–Pb saturates faster than pp. This may be due to cold nuclear (CNM) effect or collectivity or present of saturation effect in p–Pb collisions.

The most important aspects of these measurements by ALICE is to understand the the system formation in high-multiplicity pp collisions and hence provide inputs to study the QGP in heavy-ion collisions.

- **PYTHIA8 Study of J/ψ :** The pp collisions at the LHC energies, MPI drives the the quarkonia production with a little effect of color reconnection (CR) at the final state. CR has more effect at high multiplicity and higher collision energies. The $\psi(2S)$ and J/ψ are produced almost in equal proportion in each multiplicity bins. We found that $N_{ch} > 20$ is the threshold number for charged-particle multiplicity in the final state for pp collisions in order to observe a substantial MPI effects on charmonia production.

- **Baryon Stopping:** The discussed methodology of stopped proton estimation will help to disentangle “stopped-protons” and “produced protons”, which will be useful to study their role to the criticality in QCD phase diagram. Experimentally, it is unable to tag a proton from production or stopping. Therefore, it is suggested that while quoting the fluctuation results from net-proton multiplicity distribution, a systematic uncertainty may be added by using the Monte Carlo simulations and the results of the study from this thesis to quantify the effect of stopping on the fluctuations in their respective acceptance.
- **Tsallis non-extensive statistics:** We observe a similar mass dependent trend in most peripheral AA and pp collisions, hints that the system formed in both the cases have similarity in terms of thermodynamic Tsallis parameters. A mass dependent differential freeze out scenario has been observed in peripheral AA and pp collisions.

Now-a-days, the multiplicity dependence study of particle production at the LHC energies is a hot topic within high-energy scientific community. Therefore, the present measurement of J/ψ with multiplicity is definitely an important contribution in that direction as far as J/ψ suppressions is concern. There are lots of scope to extend the present analysis in different direction. For example; multiplicity dependence study of J/ψ suppression across collision systems: pp, p–Pb and Pb–Pb, multiplicity dependence study of other vector meson like χ_c , η_c , multiplicity dependence study of J/ψ polarization etc. are potential problems. The contribution to the current measurement of J/ψ from B-hadron decays as a function of multiplicity is unknown. The study of the prompt and non-prompt J/ψ production with multiplicity will be helpful to understand the role of initial and final state effects. Further, the methodology proposed to disentanglement of stopped and produced protons will be a crucial model to apply in the upcoming Compressed Baryonic Matter (CBM) experiment, which will operate at very low energies where baryon stopping will play a major role. The present study of particle spectra using Tsallis non-extensive statistics may extend to a more differential study involving recently run different colliding

energies as well as more particle species to have a complete and distinct picture of the observed scenario.

Chapter 8

Appendix

8.1 Tsallis Distribution (V , T , q , μ)

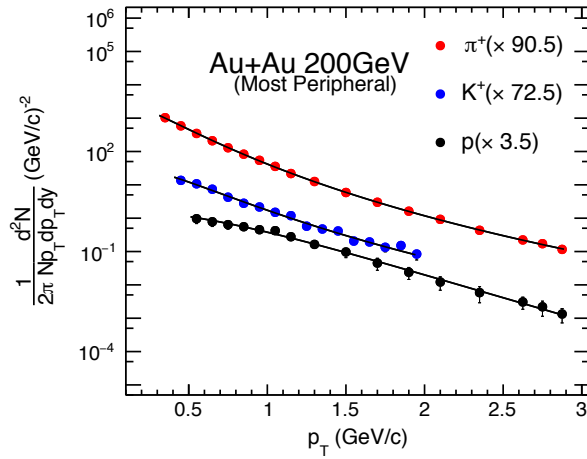


Figure 8.1. (color online) Fitting of invariant p_T spectra with Tsallis distribution including chemical potential using Eq.6.11 for π^+ [203], K^+ [203], p [203] in most peripheral Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV. Symbols represent the data points and the line is the fit function [189].

Au+Au 200 GeV (Peripheral)					
Particle	χ^2/ndf	V (fm) ³	T (GeV)	q	μ (GeV)
π^+	0.191	2125.93 $\pm$ 56.06	0.094 $\pm$ 0.004	1.113 $\pm$ 0.004	0.005 $\pm$ 0.0003
π^-	0.325	1895.78 $\pm$ 275.34	0.097 $\pm$ 0.004	1.110 $\pm$ 0.004	0.008 $\pm$ 0.0003
K^+	1.415	63.64 $\pm$ 12.60	0.089 $\pm$ 0.021	1.128 $\pm$ 0.025	0.086 $\pm$ 0.009
K^-	1.309	113.82 $\pm$ 68.83	0.090 $\pm$ 0.012	1.126 $\pm$ 0.023	0.085 $\pm$ 0.003
p	0.170	10.01 $\pm$ 3.71	0.213 $\pm$ 0.029	1.026 $\pm$ 0.024	0.310 $\pm$ 0.190
$\bar{p}$	0.111	11.62 $\pm$ 3.48	0.183 $\pm$ 0.015	1.051 $\pm$ 0.014	0.437 $\pm$ 0.103

Table 8.1. χ^2/ndf and different extracted parameters from Tsallis distribution fit(Eq. 6.11) to the p_T spectra of $\pi^\pm$, $K^\pm$, p and $\bar{p}$ for most peripheral Au+Au collisions at $\sqrt{s_{NN}}=200$ GeV.

8.2 Tsallis Distribution (V, T, q, β):

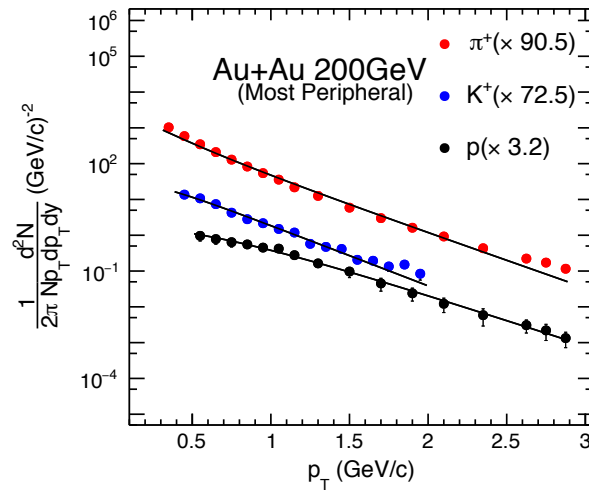


Figure 8.2. (color online) Fitting of invariant p_T spectra with Tsallis distribution including radial flow using Eq. 6.2.2 for π^+ [203], K^+ [203], p [203] in most peripheral Au+Au collisions at $\sqrt{s_{NN}}=200$ GeV [189].

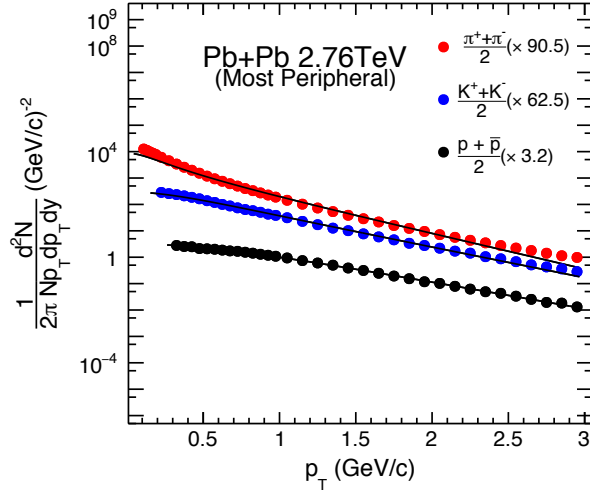


Figure 8.3. (color online) Fitting of invariant p_T spectra with Tsallis distribution including radial flow using Eq. 6.2.2 for $\frac{\pi^++\pi^-}{2}$ [205], $\frac{k^++k^-}{2}$ [205], $\frac{p+\bar{p}}{2}$ [205] in most peripheral Pb+Pb collisions at $\sqrt{s_{NN}}=2.76$ TeV; Symbols represent the data points and the line is the fit function [189].

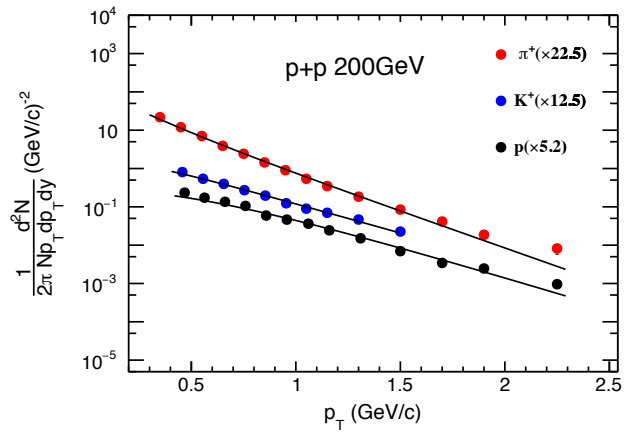


Figure 8.4. (color online) Fitting of invariant p_T spectra with Tsallis distribution including radial flow using Eq. 6.2.2 for π^+ [204], K^+ [204], p [204] in $p + p$ collisions at $\sqrt{s_{NN}}= 200$ GeV. Symbols represent the data points and the line is the fit function [189].

Au+Au 200 GeV (Peripheral)					
Particle	χ^2/ndf	$V (fm)^3$	$T (GeV)$	β	q
π^+	16.558	302.680 ± 7.591	0.152 ± 0.001	0.475 ± 0.013	1.021 ± 0.004
K^+	2.2461	30.005 ± 1.676	0.154 ± 0.044	0.363 ± 0.008	1.020 ± 0.021
p	0.1825	17.731 ± 1.952	0.247 ± 0.000	0.147 ± 0.018	1.004 ± 0.041
$p + p$ 200 GeV					
π^+	1.370	60.260 ± 0.506	0.123 ± 0.015	0.455 ± 0.015	1.025 ± 0.015
K^+	0.996	7.914 ± 0.878	0.160 ± 0.004	0.400 ± 0.013	1.027 ± 0.038
p	3.144	25.970 ± 0.667	0.194 ± 0.017	0.258 ± 0.019	1.010 ± 0.010

Pb+Pb 2.76 TeV (Peripheral)					
Particle	χ^2/ndf	$V (fm)^3$	$T (GeV)$	β	q
$\frac{\pi^+ + \pi^-}{2}$	5.657	444.714 ± 7.931	0.185 ± 0.008	0.480 ± 0.028	1.027 ± 0.006
$\frac{K^+ + K^-}{2}$	1.025	149.038 ± 11.465	0.200 ± 0.133	0.460 ± 0.021	1.023 ± 0.010
$\frac{p + \bar{p}}{2}$	0.258	14.507 ± 1.107	0.299 ± 0.090	0.260 ± 0.055	1.013 ± 0.024
$p + p$ 2.76 TeV					
$\frac{\pi^+ + \pi^-}{2}$	18.290	191.039 ± 15.890	0.116 ± 0.003	0.601 ± 0.013	1.038 ± 0.004
$\frac{K^+ + K^-}{2}$	8.006	10.164 ± 1.097	0.197 ± 0.005	0.433 ± 0.016	1.023 ± 0.005
$\frac{p + \bar{p}}{2}$	7.596	1.839 ± 0.256	0.224 ± 0.006	0.310 ± 0.014	1.014 ± 0.004

Table 8.2. χ^2/ndf and different extracted parameters from Tsallis distribution fit(Eq. 6.13) to the p_T spectra of (a) π^+ , K^+ and p for most peripheral Au+Au collisions and $p + p$ collisions at $\sqrt{s_{NN}} = 200$ GeV; (b) $\frac{\pi^+ + \pi^-}{2}$, $\frac{K^+ + K^-}{2}$ and $\frac{p + \bar{p}}{2}$ for most peripheral Pb+Pb collisions and $\frac{\pi^+ + \pi^-}{2}$, $\frac{K^+ + K^-}{2}$ and $\frac{p + \bar{p}}{2}$ for $p + p$ collisions at $\sqrt{s_{NN}} = 2.76$ TeV.

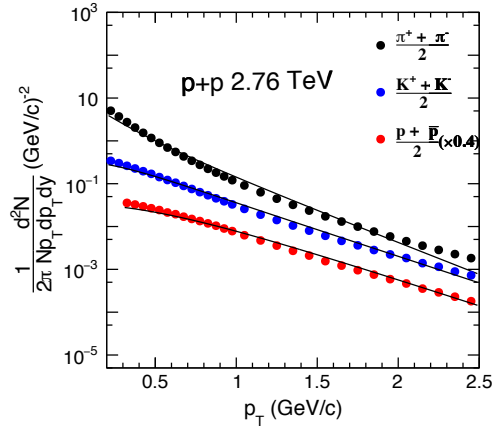


Figure 8.5. (color online) Fitting of invariant p_T spectra with Tsallis distribution including radial flow using Eq. 6.2.2 for $\frac{\pi^+ + \pi^-}{2}$ [205], $\frac{K^+ + K^-}{2}$ [205], $\frac{p + \bar{p}}{2}$ [205] in $p + p$ collisions at $\sqrt{s_{NN}} = 2.76$ TeV. Symbols represent the data points and the line is the fit function [189].

8.3 Run Numbers

The run numbers used for the analysis corresponding to each periods are en-listed below,

LHC16h (72 runs)

255467, 255466, 255465, 255463, 255447, 255442, 255440, 255415, 255402, 255398, 255352, 255351, 255350, 255283, 255280, 255276, 255275, 255256, 255255, 255253, 255252, 255251, 255249, 255248, 255247, 255242, 255240, 255182, 255180, 255177, 255176, 255173, 255171, 255167, 255162, 255159, 255154, 255111, 255091, 255086, 255085, 255082, 255079, 255076, 255075, 255074, 255073, 255071, 255068, 255042, 255010, 255009, 255008, 254984, 254983, 254654, 254653, 254652, 254651, 254649, 254648, 254646, 254644, 254640, 254632, 254630, 254629, 254621, 254608, 254606, 254604, 254419

LHC16j (49 runs)

256420, 256418, 256417, 256415, 256373, 256372, 256371, 256368, 256366, 256365, 256364, 256363, 256362, 256361, 256356, 256311, 256307, 256302, 256298, 256297, 256295, 256292, 256290, 256289, 256287, 256284, 256283, 256282, 256281, 256231, 256228, 256227, 256223, 256222, 256219, 256215, 256213, 256212, 256210, 256169, 256204, 256161, 256158, 256157, 256156, 256149, 256148, 256147, 256146

LHC16k (171 runs)

258537, 258499, 258498, 258477, 258456, 258454, 258452, 258426, 258393, 258391, 258388, 258387, 258359, 258336, 258332, 258307, 258306, 258303, 258302, 258301, 258299, 258280, 258278, 258274, 258273, 258271, 258270, 258258, 258257, 258256, 258204, 258203, 258202, 258197, 258178, 258117, 258114, 258113, 258109, 258108, 258107, 258063, 258062, 258060, 258059, 258049, 258048, 258045, 258042, 258041, 258039, 258019, 258017, 258014, 258012, 258008, 257989, 257986, 257979, 257963, 257960, 257958, 257957, 257939, 257937, 257936, 257932, 257912, 257901, 257893, 257892, 257737, 257735, 257734, 257733, 257727, 257725, 257724, 257697, 257694, 257688, 257687, 257685, 257684, 257682, 257644, 257642, 257636, 257635, 257632,

257630, 257606, 257605, 257604, 257601, 257595, 257594, 257592, 257590,
257588, 257587, 257566, 257565, 257564, 257563, 257562, 257561, 257560,
257541, 257540, 257531, 257530, 257492, 257491, 257490, 257488, 257487,
257474, 257468, 257457, 257433, 257364, 257358, 257330, 257322, 257320,
257318, 257260, 257224, 257095, 257092, 257086, 257084, 257083, 257082,
257080, 257077, 257071, 257026, 257021, 257012, 257011, 256944, 256942,
256941, 256697, 256695, 256694, 256691, 256684, 256681, 256677, 256676,
256658, 256620, 256619, 256591, 256567, 256565, 256564, 256561, 256560,
256557, 256556, 256554, 256552, 256512, 256510, 256506, 256504, 256399

LHC16o (101 runs)

264035, 264033, 263985, 263984, 263981, 263979, 263978, 263977, 263923,
263920, 263917, 263916, 263905, 263866, 263863, 263861, 263830, 263829,
263824, 263823, 263813, 263810, 263803, 263793, 263792, 263790, 263787,
263786, 263785, 263784, 263744, 263743, 263741, 263739, 263738, 263737,
263691, 263690, 263689, 263682, 263662, 263657, 263654, 263653, 263652,
263647, 263529, 263497, 263496, 263490, 263487, 263332, 262858, 262855,
262853, 262849, 262847, 262844, 262842, 262841, 262778, 262777, 262776,
262768, 262760, 262727, 262725, 262723, 262719, 262717, 262713, 262705,
262635, 262632, 262628, 262594, 262593, 262583, 262578, 262574, 262572,
262571, 262570, 262569, 262568, 262567, 262563, 262537, 262533, 262532,
262528, 262492, 262487, 262451, 262430, 262428, 262424, 262423, 262422,
262419, 262418

LHC16p (39 runs)

264347, 264346, 264345, 264341, 264336, 264312, 264306, 264305, 264281,
264279, 264277, 264273, 264267, 264266, 264265, 264264, 264262, 264261,
264260, 264259, 264238, 264233, 264232, 264198, 264197, 264194, 264188,
264168, 264164, 264138, 264137, 264129, 264110, 264109, 264086, 264085,
264082, 264078, 264076

8.4 $\langle N_{Trk} \rangle(z_v)$ equalization on the basis of beam condition

Example of an filling scheme: 50ns_480b+1small_424_12_468_36bpi15inj

- 50ns: bunch spacing
- 480b: bunches per beam
- 424: colliding bunches in the interaction Points 1 (ATLAS) and 5 (CMS)
- 12: colliding bunches in the IP 2 (ALICE)
- 468: colliding bunches in IP8 (LHCb)
- 36bpi15inj: 36 bunches per injection and 15 injections per beam

LHC16p

Filling scheme is **25ns_2220b_2208_1940_2036_96bpi_24inj** for all the LHC 16p run numbers.

LHC16h

(1) **25ns_2040b_2028_1697_1712_72bpi_30inj**

LHC 16h: 255469, 255467, 255466, 255465, 255463, 255447, 255442, 255440, 255421, 255420, 255419, 255418, 255415, 255407, 255402, 255398

(2) **25ns_1824b_1812_1539_1571_72bpi_27inj**

LHC 16h: 255352, 255351, 255350, 255283, 255280, 255276, 255275

(3) **25ns_1752b_1740_1470_1499_72bpi_26inj**

LHC 16h: 255256, 255255, 255253, 255252, 255251, 255249, 255248, 255247, 255242, 255240, 255182, 255181, 255180, 255177, 255176, 255174, 255173, 255171, 255167, 255162, 255159, 255154, 255111

(4) **25ns_1465b_1453_1122_1153_72bpi_23inj**

LHC 16h: 255091, 255086, 255085, 255082, 255079

(5) **25ns_601b_589_552_552_72bpi_11inj_950ns**

LHC 16h: 254984, 254983

(6) **25ns_1177b_1165_990_984_72bpi_19inj**

LHC 16h: 254654, 254653, 254652, 254651, 254649, 254648, 254646, 254644, 254640, 254632, 254630, 254629, 254621, 254608, 254606, 254604

LHC 16j

(1) **25ns_2040b_2028_1697_1712_72bpi_30inj LHC 16j:** 256420, 256418, 256417, 256415, 256373, 256372, 256371, 256368, 256366, 256365, 256364, 256363, 256362, 256361, 256357, 256356, 256311, 256309, 256307, 256302, 256299, 256298, 256297, 256295, 256292, 256290, 256289, 256287, 256284, 256283, 256282, 256281, 256231, 256228, 256227, 256225, 256223, 256222, 256219, 256215, 256213, 256212, 256210, 256207, 256204

(2) **25ns_602b_590_552_552_72bpi_12inj_950ns LHC 16j:** 256162, 256161, 256158, 256157, 256156, 256152, 256149, 256148, 256147, 256146

LHC 16k

(1) **25ns_2076b_2064_1681_1772_96bpi_23inj**

258537, 258499, 258498, 258477, 258456, 258454, 258452, 258426, 258393, 258391, 258388, 258387, 258359, 258336, 258332, 258307, 258306, 258303, 258302, 258301, 258299, 258280, 258278, 258274, 258273, 258271, 258270, 258258, 258257, 258256, 258204, 258203, 258202, 258198, 258197, 258178, 258117, 258114, 258113, 258109, 258108, 258107, 258063, 258062, 258060, 258059, 258053, 258049, 258048, 258045, 258042, 258041, 258039, 258019, 258017, 258014, 258012, 258008, 258003, 257992, 257989, 257986, 257979, 257963, 257960, 257958, 257957, 257939, 257937, 257936, 257932, 257912, 257901, 257893, 257892, 257855, 257853, 257851, 257850, 257804, 257803, 257800, 257799, 257798, 257797, 257773, 257765, 257757, 257754, 257737, 257735, 257734, 257733, 257727, 257725, 257724, 257697, 257694, 257692, 257691, 257689, 257688, 257687, 257685, 257684, 257682, 257644, 257642, 257636, 257635, 257632, 257630, 257606, 257605, 257604, 257601, 257595, 257594, 257592, 257590, 257588, 257587, 257566, 257565, 257564, 257563, 257562, 257561, 257560, 257541, 257540, 257539, 257537, 257531, 257530, 257492, 257491, 257490, 257488, 257487, 257474, 257468, 257457, 257433, 257364, 257358, 257330, 257322, 257320, 257318, 257260, 257224, 257209,

257206, 257204, 257145, 257144, 257142, 257141, 257140, 257139, 257138,
257137, 257136, 257100, 257095, 257092, 257086, 257084, 257083, 257082,
257080, 257077, 257071, 257028, 257026, 257021, 257012, 257011

(2) 25ns_2040b_2028_1698_1715_72bpi_30inj

256944, 256942, 256941, 256697, 256695, 256694, 256692, 256691, 256684,
256681, 256677, 256676, 256658, 256620, 256619, 256592, 256591, 256589,
256567, 256565, 256564, 256562, 256561, 256560, 256557, 256556, 256554,
256552, 256514, 256512, 256510, 256506, 256504

LHC 16o

(1) 25ns_2220b_2208_1940_2036_96bpi_24inj

LHC16o!264035, 264033, 263985, 263984, 263981, 263979, 263978, 263977,
263923, 263920, 263917, 263916, 263905, 263866, 263863, 263861, 263830,
263829, 263824, 263823, 263814, 263813, 263810, 263803, 263793, 263792,
263790, 263787, 263786, 263785, 263784, 263744, 263743, 263741, 263739,
263738, 263737, 263691, 263690, 263689, 263682, 263663, 263662, 263657,
263654, 263653, 263652, 263647, 263529, 263497, 263496, 263490, 263487,
263332, 263331, 262858, 262855, 262853, 262849, 262847, 262844, 262842,
262841, 262778, 262777, 262776, 262768, 262760, 262727, 262725, 262723,
262719, 262717, 262713, 262708, 262706, 262705, 262635, 262632, 262628,
262624, 262594, 262593, 262583, 262578, 262574, 262572, 262571, 262570,
262569, 262568, 262567, 262563, 262537, 262533, 262532, 262528

(2) 25ns_1177b_1165_1047_1092_96bpi_15inj

262492, 262490, 262489, 262487

(3) 25ns_601b_589_523_544_96bpi_11inj

262451, 262450

(4) 25ns_169b_157_114_120_48bpi_6inj

262430, 262428, 262426, 262425, 262424, 262423, 262422, 262419, 262418

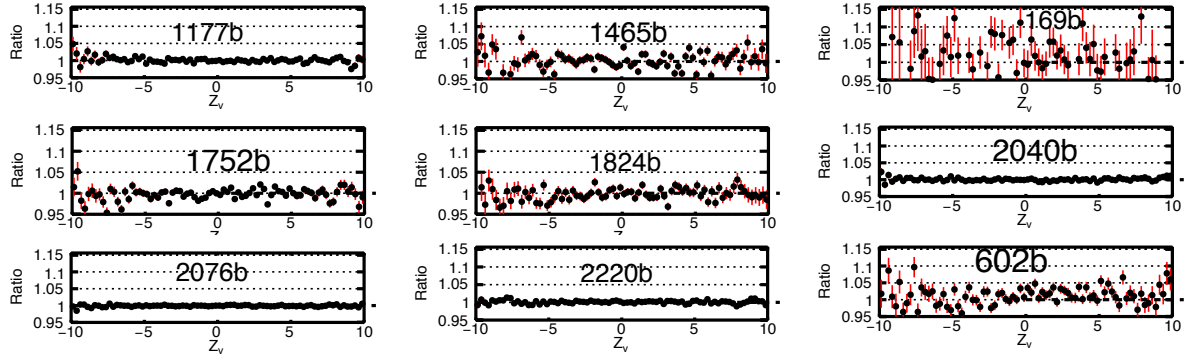


Figure 8.6. Ratio of CMUL7 , $\langle N_{Trk} \rangle$ vs. z_v profile of each beam condition w.r.t integrated one, showing not much difference across the beam conditions. (16h+16j+16k+16o+16p used in the calculation) [116].

8.5 Vertex QA Efficiency calculation

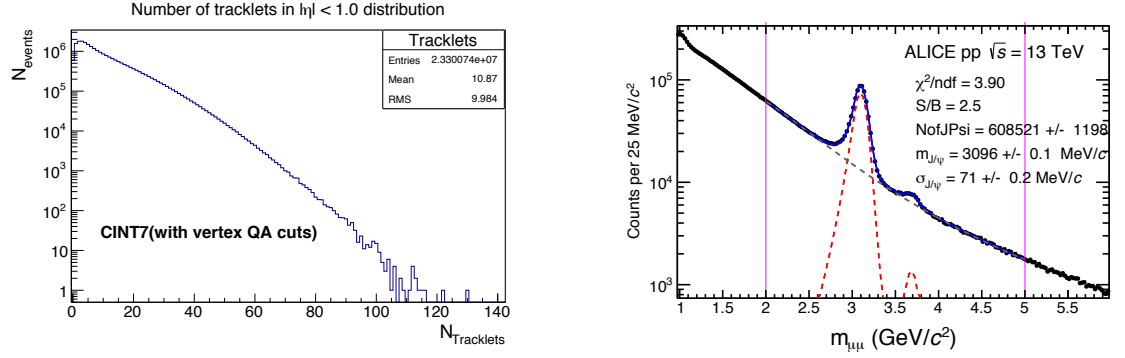


Figure 8.7. Number of CINT7 events(Left) and number of J/ψ (Reght) with vertex QA cuts (For LHC 16h + 16j + 16k + 16o + 16p periods) [116].

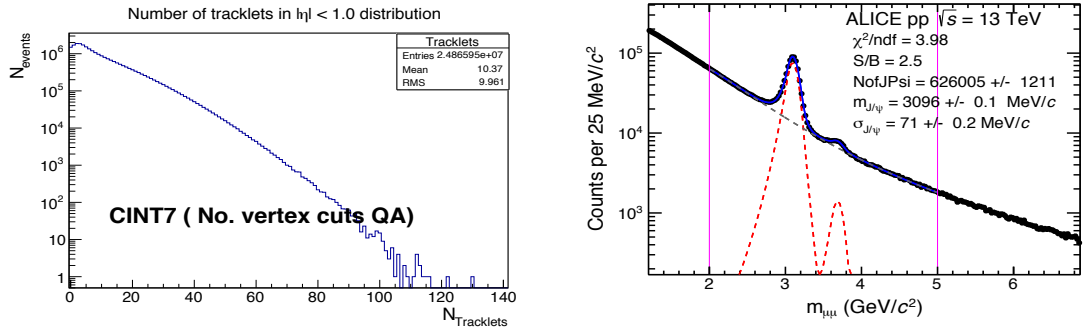


Figure 8.8. Number of CINT7 events(Left) and number of J/ψ (Reght) with out vertex QA cuts (For LHC 16h + 16j + 16k + 16o + 16p periods) [116].

8.6 $INEL > 0$ Efficiency comparison for “ $N_{ch} > 0$ ” and “ $N_{Trk} > 0$ ” condition

- $N_{ch} > 0$ condition:: At least one physical primary charged particle in $|\eta| < 1.0$.
- $N_{Trk} > 0$ condition:: At least one Tracklet in $|\eta| < 1.0$.

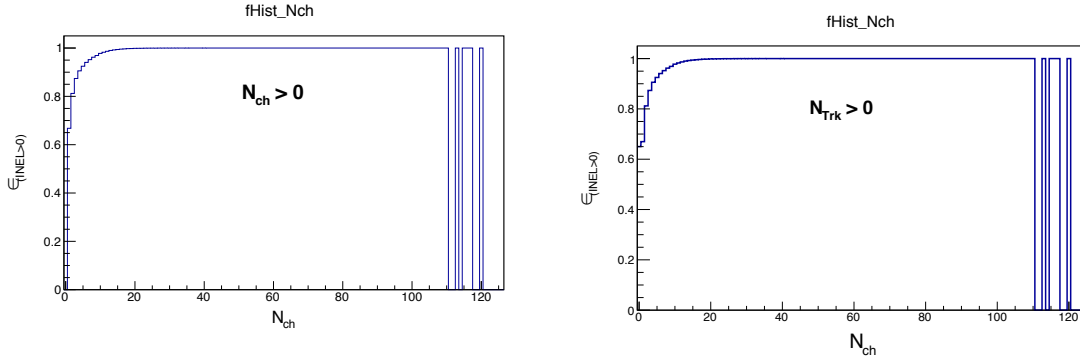


Figure 8.9. Evolution of $INEL > 0$ efficiency as a function of N_{ch} for $N_{ch} > 0$ and $N_{Trk} > 0$ condition.(Tested for LHC 16p only) [116].

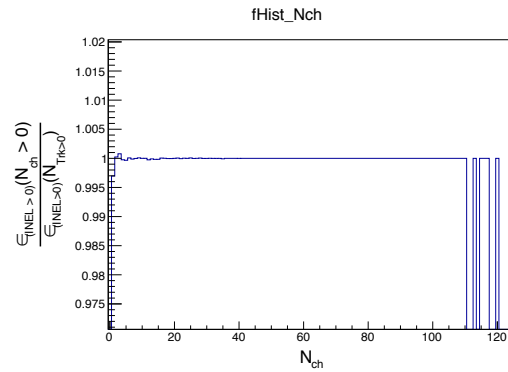


Figure 8.10. Ratio of $INEL > 0$ efficiency for $N_{ch} > 0$ and $N_{Trk} > 0$ condition.(Tested for LHC 16p only) [116].

8.7 Data and MC comparison “with $N_{ch} > 0$ ” and “with out $N_{ch} > 0$ ” cuts

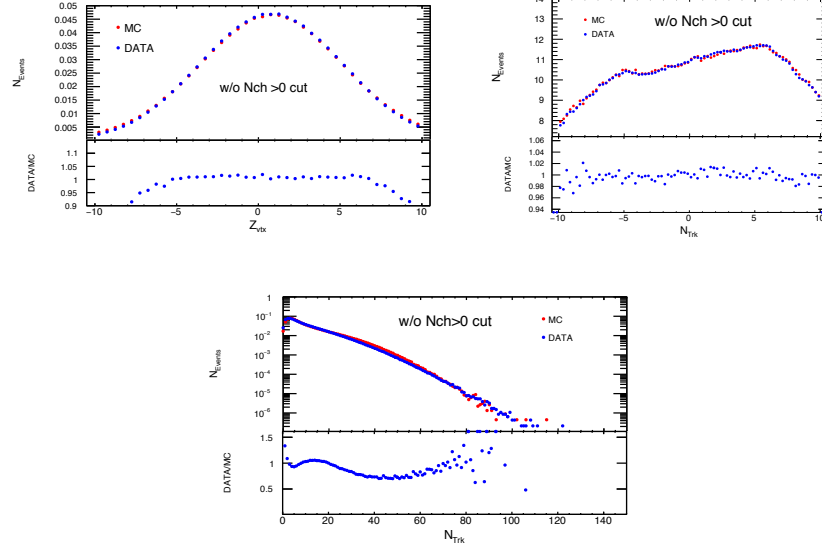


Figure 8.11. Comparison of data and PYTHIA8 for vertex, $\langle N_{Trk} \rangle$ Vs. Z_{Vertex} distribution and tracklets, with out $N_{ch} > 0$ cut (LHC 16h anchored data only used) [116].

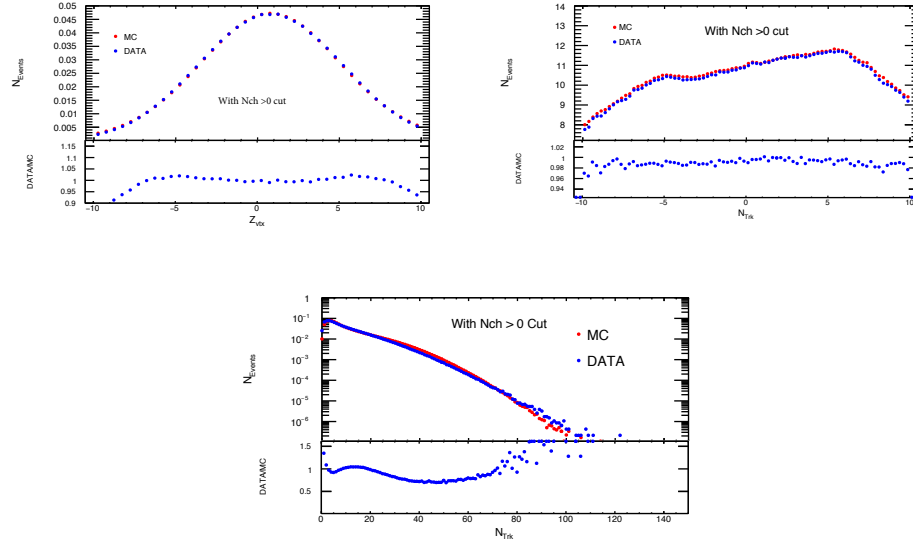


Figure 8.12. Comparison of data and PYTHIA8 for vertex, $\langle N_{Trk} \rangle$ Vs. Z_{Vertex} distribution and tracklets, with $N_{ch} > 0$ cut (LHC 16h anchored data only used) [116].

8.8 Signal Loss due to MB condition

We have calculated the signal loss due to MB condition. There is possibility to still have $INEL > 0$ events which do not fire MB(CMUL7), which may contains signal(here, J/ψ). This can be calculated as follow,

$$\epsilon_{INEL>0}^{J/\psi} = \frac{\text{Dimuon Events (CMUL7)}}{\text{Dimuon Events (No Trigger)}} \quad (8.1)$$

To be noted that, we have not applied any event cuts as like $INEL > 0$ efficiency calculation.

Reference as Maximum			
Number of dimuon events events with and with-out CMUL7 in multiplicity bins			
Multiplicity Class	With CMUL7	No trigger	$\epsilon_{INEL>0}^{J/\psi}$
Integrated	24118870	24193600	0.9969 ± 0.0003
1.5 - 8.0	2281518	2288825	0.9968 ± 0.0009
9.0 - 14.0	3326303	3335718	0.9972 ± 0.0008
15.0 - 20.0	3875528	3886517	0.9972 ± 0.0007
21.0 - 25.0	3165405	3174371	0.9971 ± 0.0008
26.0 - 33.0	4253084	4265408	0.9971 ± 0.0007
34.0 - 41.0	2916812	2925256	0.9971 ± 0.0008
42.0 - 50.0	1875583	1881104	0.9971 ± 0.001
51.0 - 60.0	954139	956901	0.9971 ± 0.0014
61.0 - 80.0	482427	483977	0.9968 ± 0.0020
81.0 - 115.0	50575	50729	0.9969 ± 0.0063

Table 8.3. Number of dimuon events events with and with-out CMUL7 in multiplicity bins.

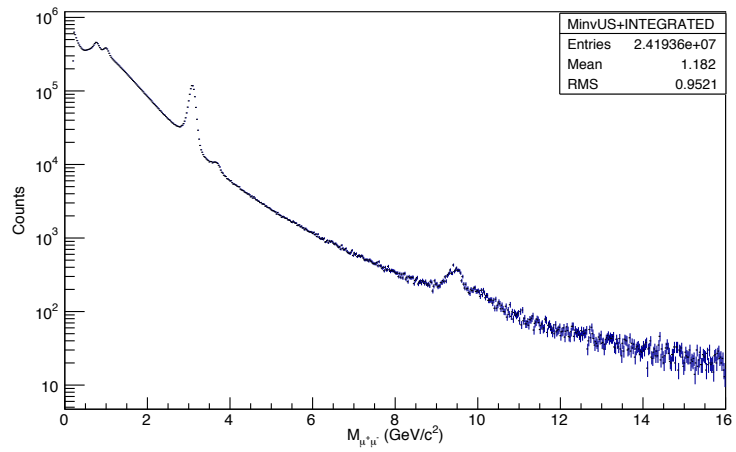


Figure 8.13. Example plot of dimuon invariant mass in integrated multiplicity. The number of entries from the invariant-masses are used to calculate the correction factor [116].

8.9 Systematic uncertainty of $N_{Trk}^{corr}-N_{ch}$ correlation

Method1(α -factor)

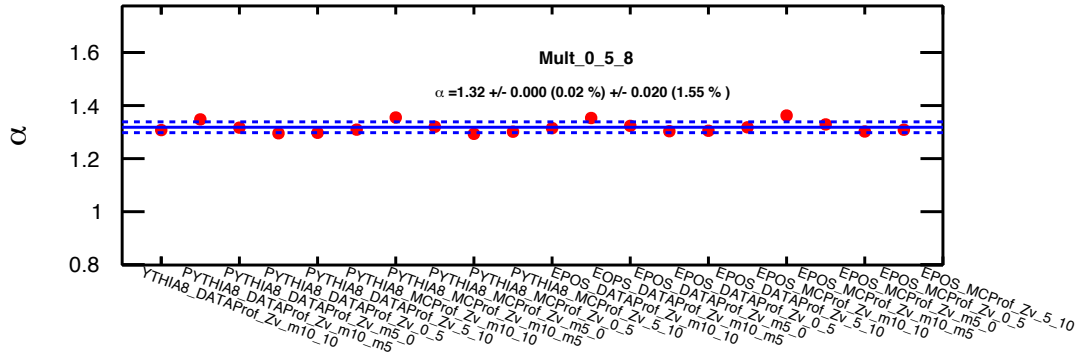


Figure 8.14. (Ref:Maximum) Value of α – *parameter* in different set of tests for the multiplicity bin (1.0, 8.0) [116].

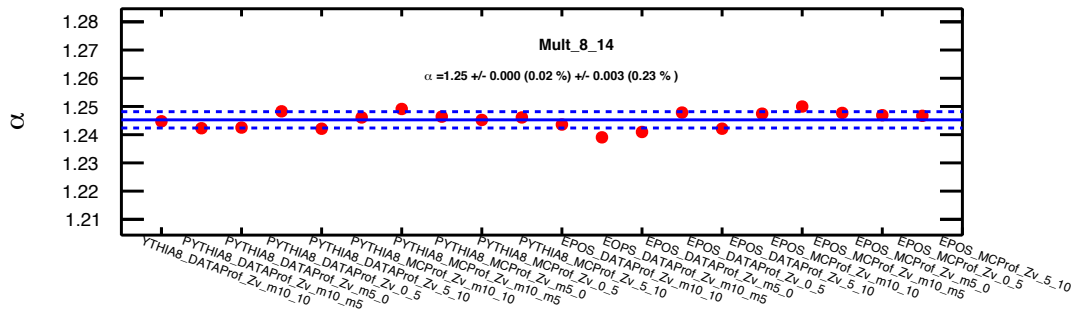


Figure 8.15. (Ref:Maximum) Value of α – *parameter* in different set of tests for the multiplicity bin (8.0, 14.0) [116].

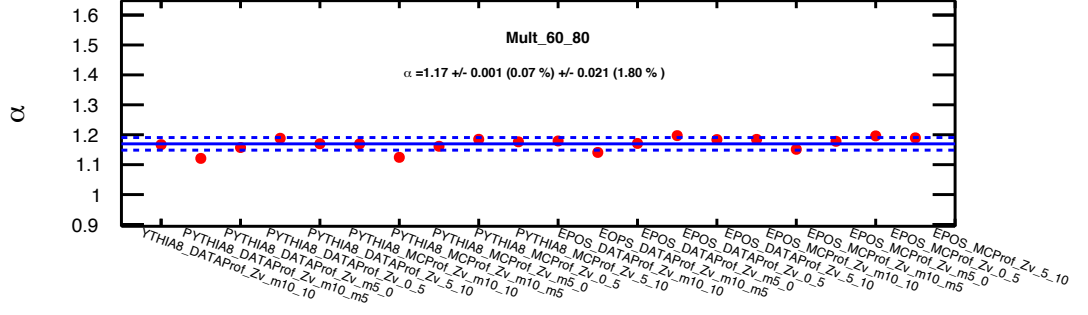


Figure 8.22. (Ref:Maximum) Value of α – *parameter* in different set of tests for the multiplicity bin (61.0, 80.0) [116].

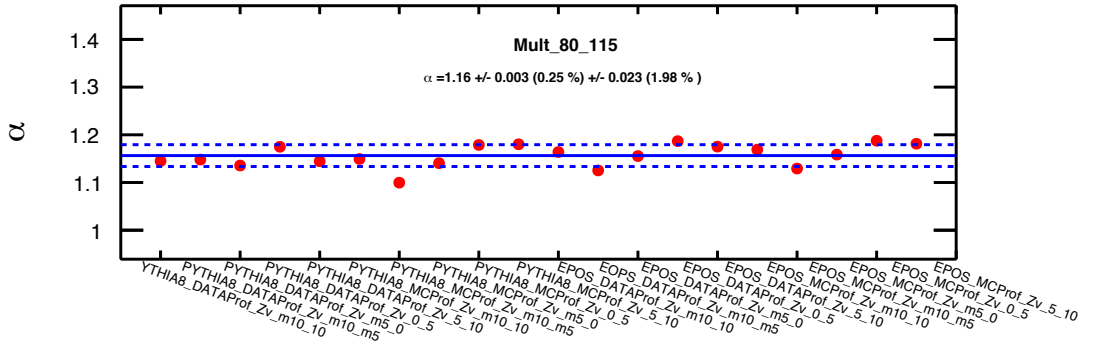


Figure 8.23. (Ref:Maximum) Value of α – *parameter* in different set of tests for the multiplicity bin (81.0, 115.0) [116].

8.9.1 Method2($\langle N_{ch} \rangle$ from add-hoc)

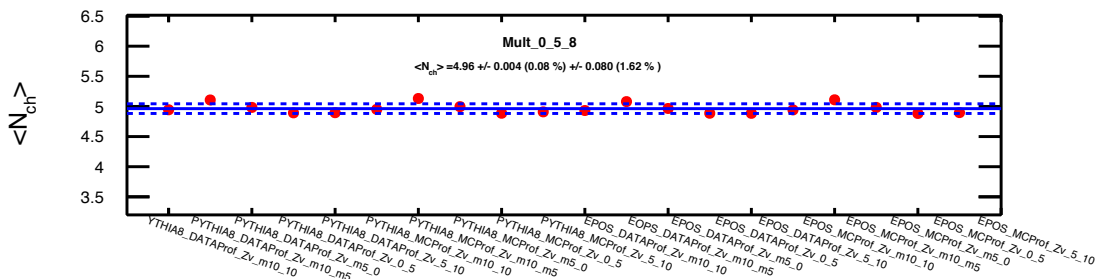


Figure 8.24. (Ref:Maximum) Value of $\langle N_{ch} \rangle$ using add-hoc polynomial in different set of tests for the multiplicity bin (1.0, 8.0) [116].

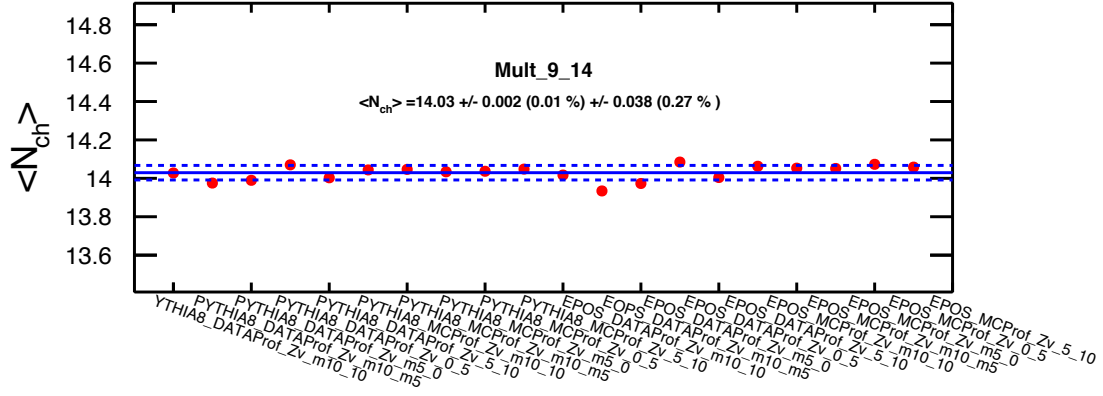


Figure 8.25. (Ref:Maximum)Value of $\langle N_{ch} \rangle$ using add-hoc polynomial in different set of tests for the multiplicity bin (9.0, 14.0) [116].

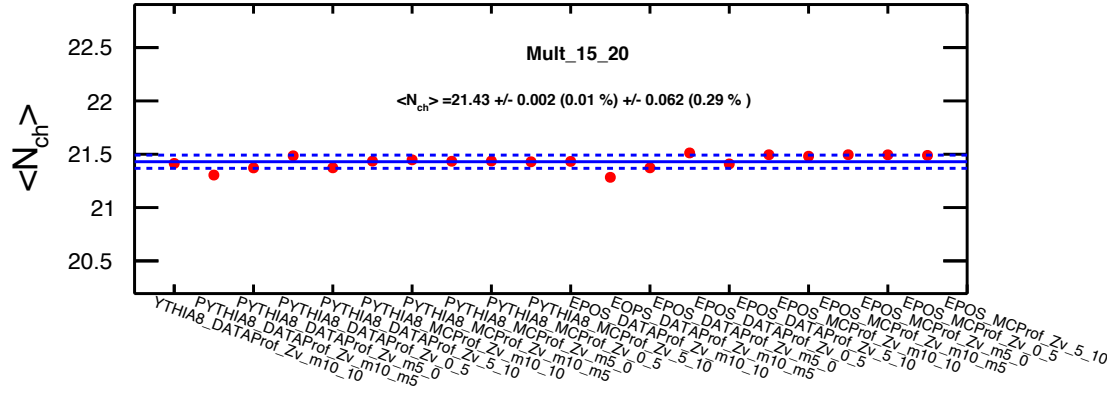


Figure 8.26. (Ref:Maximum)Value of $\langle N_{ch} \rangle$ using add-hoc polynomial in different set of tests for the multiplicity bin (15.0, 20.0) [116].

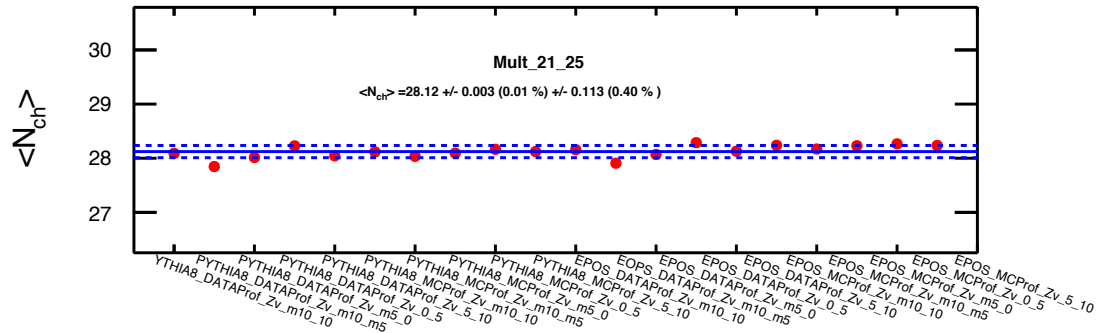
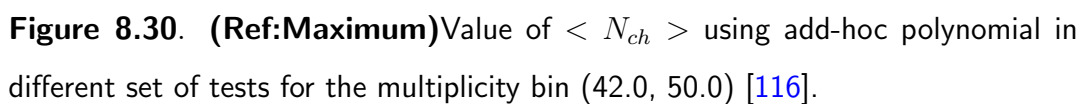
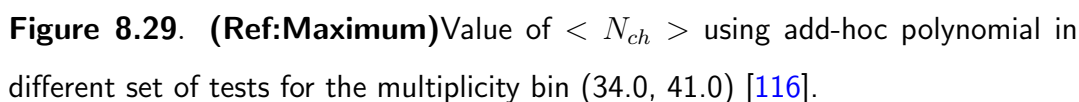
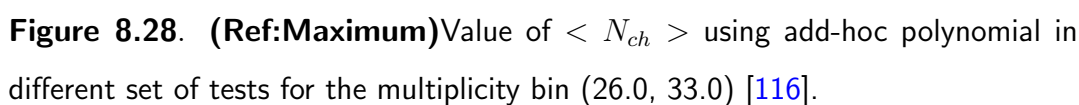


Figure 8.27. (Ref:Maximum)Value of $\langle N_{ch} \rangle$ using add-hoc polynomial in different set of tests for the multiplicity bin (21.0, 25.0) [116].



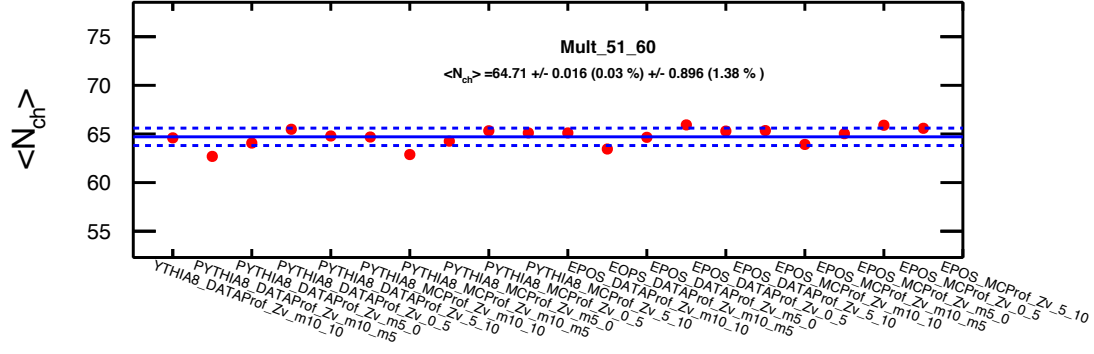


Figure 8.31. (Ref:Maximum)Value of $\langle N_{ch} \rangle$ using add-hoc polynomial in different set of tests for the multiplicity bin (51.0, 60.0) [116].

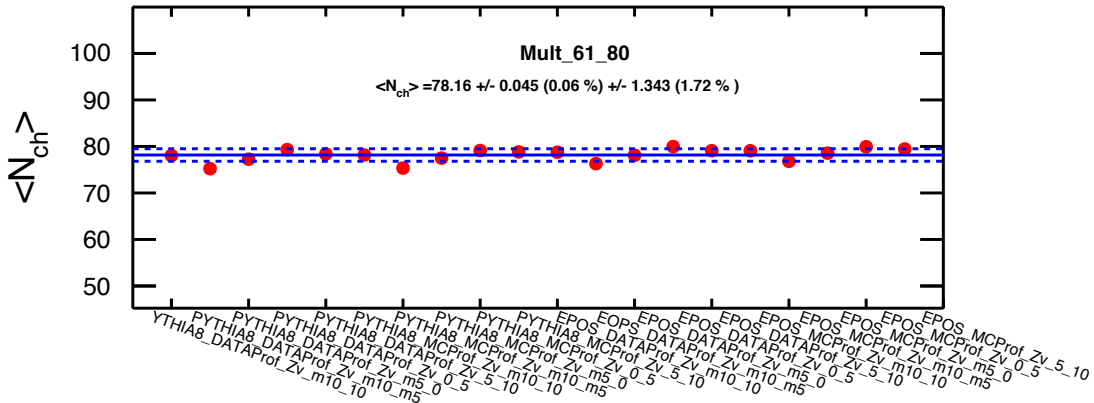


Figure 8.32. (Ref:Maximum)Value of $\langle N_{ch} \rangle$ using add-hoc polynomial in different set of tests for the multiplicity bin (61.0, 80.0) [116].

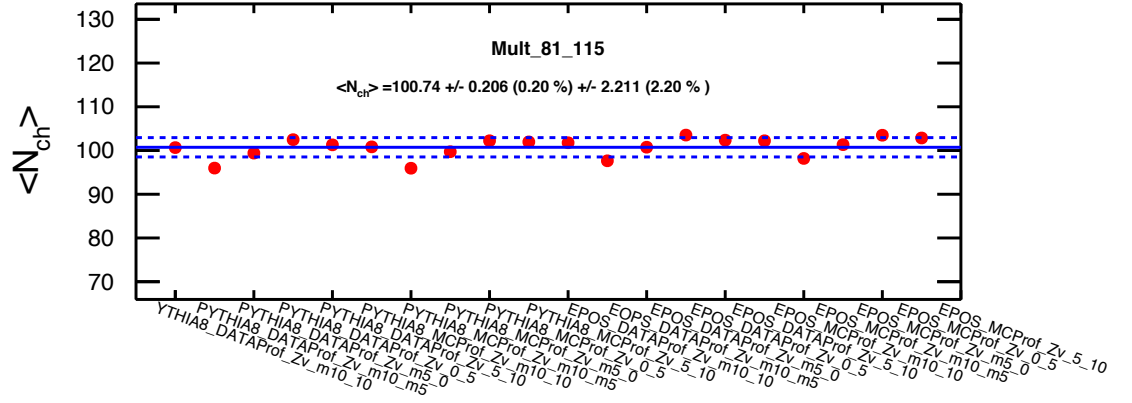


Figure 8.33. (Ref:Maximum)Value of $\langle N_{ch} \rangle$ using add-hoc polynomial in different set of tests for the multiplicity bin (81.0, 115.0) [116].

8.10 $\langle N_{ch} \rangle$ from add-hoc for Minimum as reference

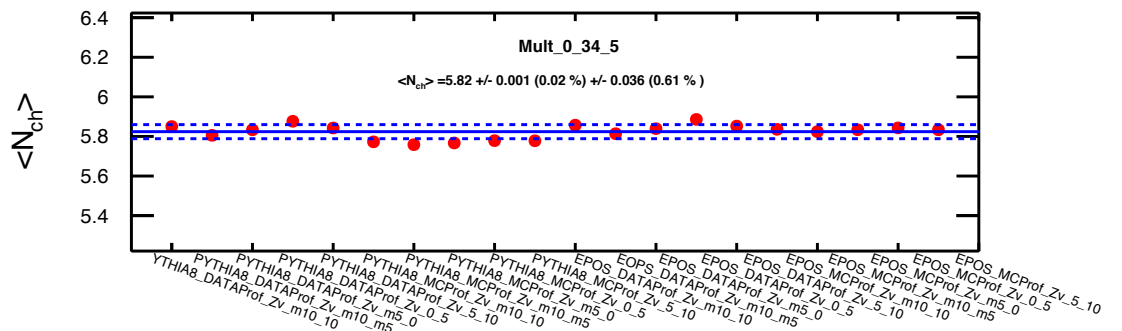


Figure 8.34. (Ref:Minimum)Value of $\langle N_{ch} \rangle$ using add-hoc polynomial in different set of tests for the multiplicity bin (0.34, 5.0) [116].

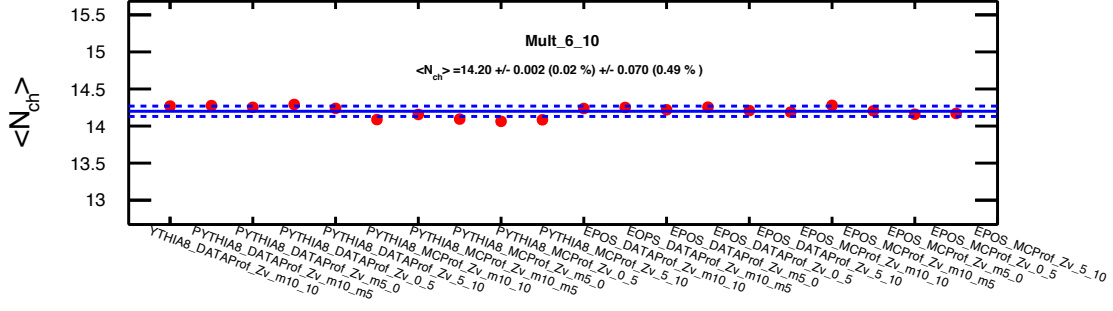


Figure 8.35. (Ref:Minimum) Value of $\langle N_{ch} \rangle$ using add-hoc polynomial in different set of tests for the multiplicity bin (6.0, 10.0) [116].

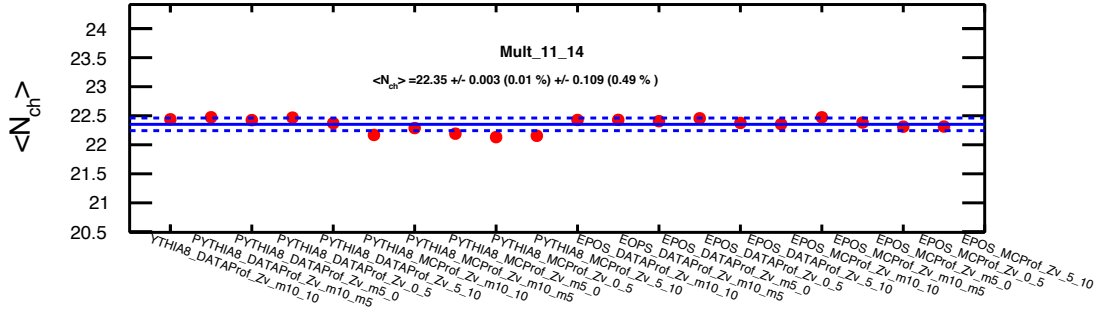


Figure 8.36. (Ref:Minimum) Value of $\langle N_{ch} \rangle$ using add-hoc polynomial in different set of tests for the multiplicity bin (11.0, 14.0) [116].

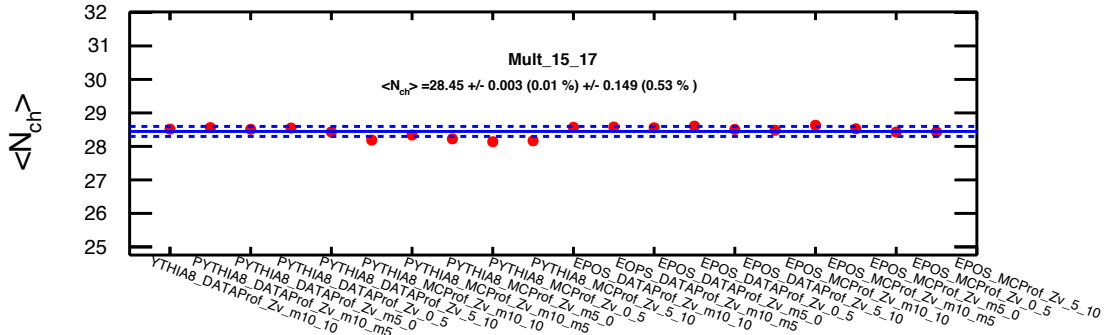


Figure 8.37. (Ref:Minimum) Value of $\langle N_{ch} \rangle$ using add-hoc polynomial in different set of tests for the multiplicity bin (15.0, 17.0) [116].

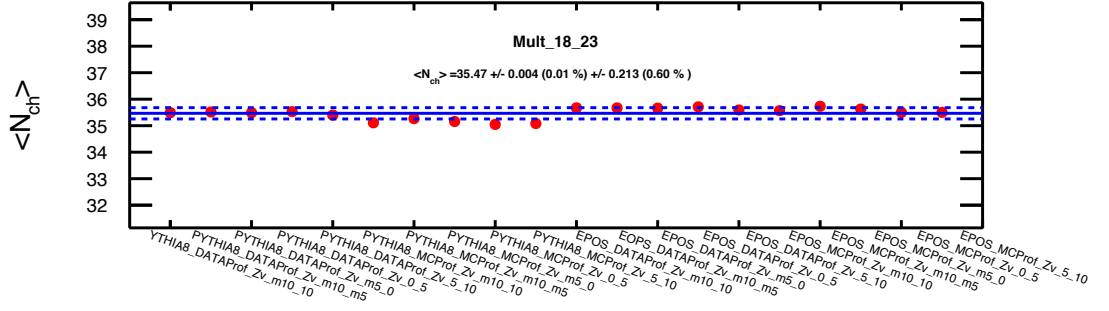


Figure 8.38. (Ref:Minimum) Value of $\langle N_{ch} \rangle$ using add-hoc polynomial in different set of tests for the multiplicity bin (18.0, 23.0) [116].

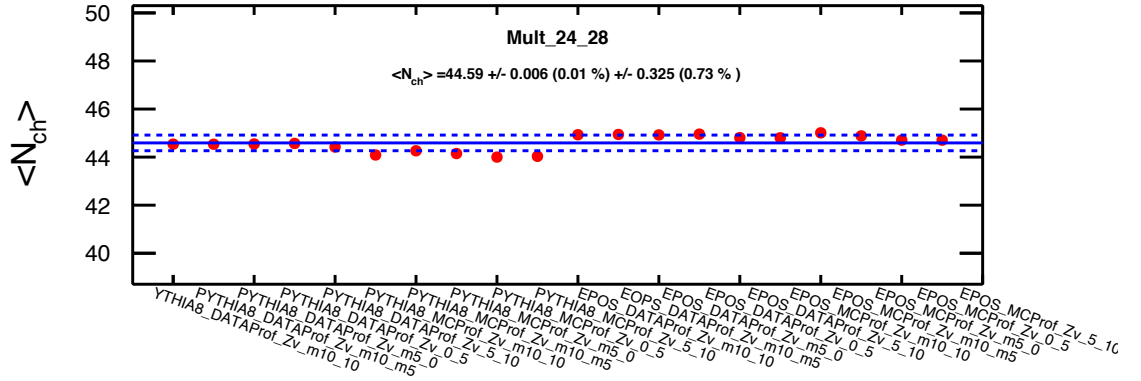


Figure 8.39. (Ref:Minimum) Value of $\langle N_{ch} \rangle$ using add-hoc polynomial in different set of tests for the multiplicity bin (24.0, 28.0) [116].

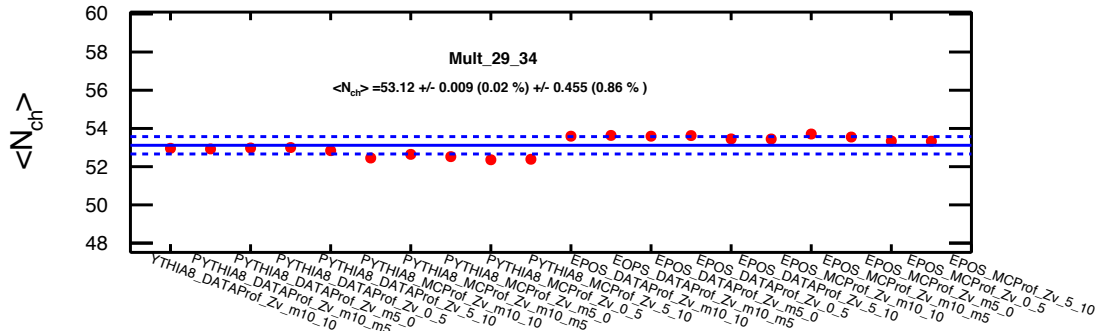


Figure 8.40. (Ref:Minimum) Value of $\langle N_{ch} \rangle$ using add-hoc polynomial in different set of tests for the multiplicity bin (29.0, 34.0) [116].

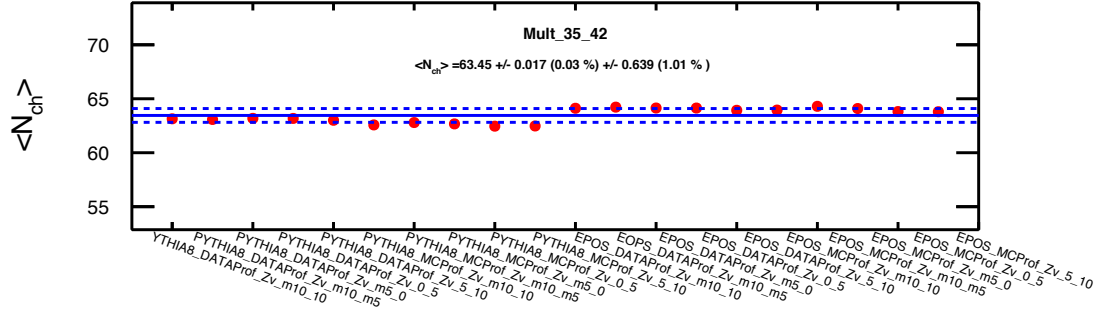


Figure 8.41. (Ref:Minimum) Value of $\langle N_{ch} \rangle$ using add-hoc polynomial in different set of tests for the multiplicity bin (35.0, 42.0) [116].

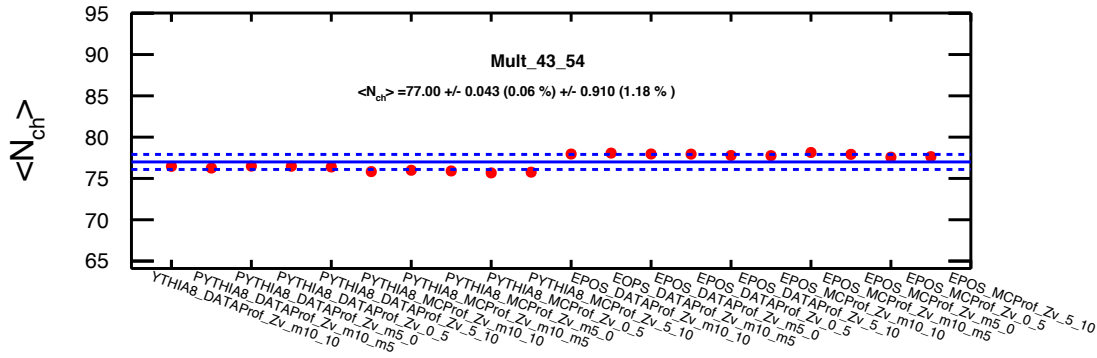


Figure 8.42. (Ref:Minimum) Value of $\langle N_{ch} \rangle$ using add-hoc polynomial in different set of tests for the multiplicity bin (43.0, 54.0) [116].

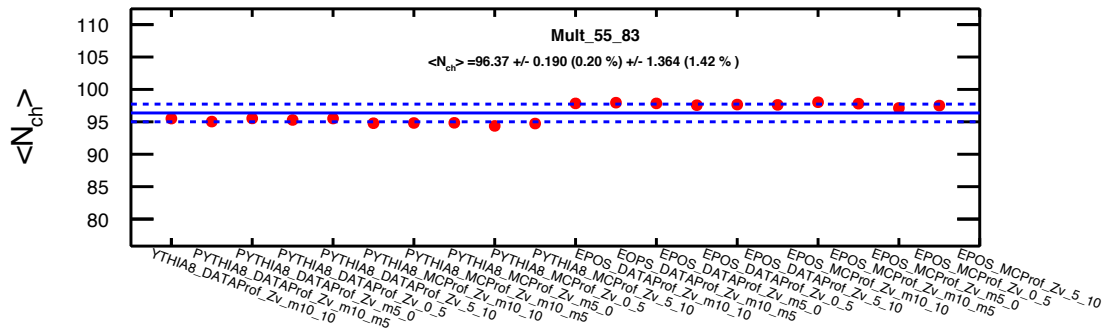


Figure 8.43. (Ref:Minimum) Value of $\langle N_{ch} \rangle$ using add-hoc polynomial in different set of tests for the multiplicity bin (55.0, 83.0) [116].

8.11 Fitting functions

CB2 function

$$f(x; \bar{x}, \sigma, \alpha, n, \alpha', n') = N \cdot \begin{cases} \exp(-\frac{(x-\bar{x})^2}{2\sigma^2}), & \text{for } \frac{x-\bar{x}}{\sigma} > -\alpha \\ A \cdot (B - \frac{x-\bar{x}}{\sigma})^{-n}, & \text{for } \frac{x-\bar{x}}{\sigma} \leq -\alpha \\ C \cdot (D + \frac{x-\bar{x}}{\sigma})^{-n'}, & \text{for } \frac{x-\bar{x}}{\sigma} \geq \alpha' \end{cases}$$

$$A = \left(\frac{n}{|\alpha|} \right)^n \cdot \exp\left(-\frac{|\alpha|^2}{2}\right)$$

$$B = \frac{n}{|\alpha|} - |\alpha|$$

$$C = \left(\frac{n'}{|\alpha'|} \right)^{n'} \cdot \exp\left(-\frac{|\alpha'|^2}{2}\right)$$

$$D = \frac{n'}{|\alpha'|} - |\alpha'|$$

NA60 function

$$\sigma = \begin{cases} p_2 & \text{for } p_9 M_0 < M < p_{10} M_0 \\ p_2 \{1 + [p_3(p_9 M_0 - M)]^{[p_4 - p_5 \sqrt{(p_9 M_0 - M)}]}\} & \text{for } M < p_9 M_0 \\ p_2 \{1 + [p_6(M - p_{10} M_0)]^{[p_7 - p_8 \sqrt{(M - p_{10} M_0)}]}\} & \text{for } M > p_{10} M_0 \end{cases}$$

$$f(M) = N \cdot \exp\left(-\frac{(M - M_0)^2}{2\sigma^2}\right)$$

VWG function

$$\sigma = \beta + \gamma \times ((x - \alpha)/\alpha)$$

$$f(x) = N \cdot \exp\left(-\frac{(x - \alpha)^2}{2\sigma^2}\right)$$

8.12 Signal systematics Plots (Ref: Maximum)

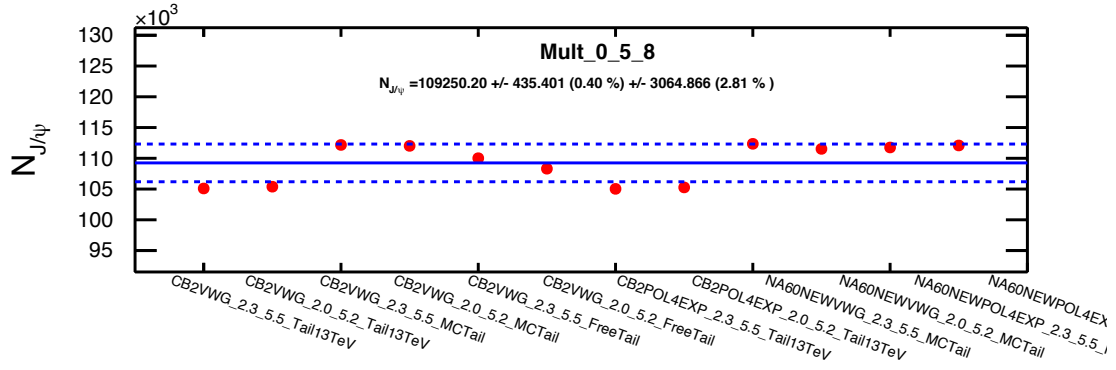


Figure 8.44. (Ref: Maximum) J/ψ yield in different set of tests for the multiplicity bin (1.0, 8.0) [116].

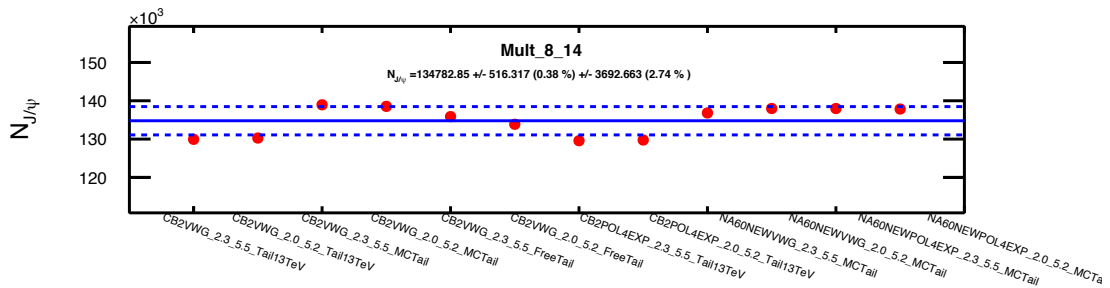


Figure 8.45. (Ref: Maximum) J/ψ yield in different set of tests for the multiplicity bin (9.0, 14.00) [116].

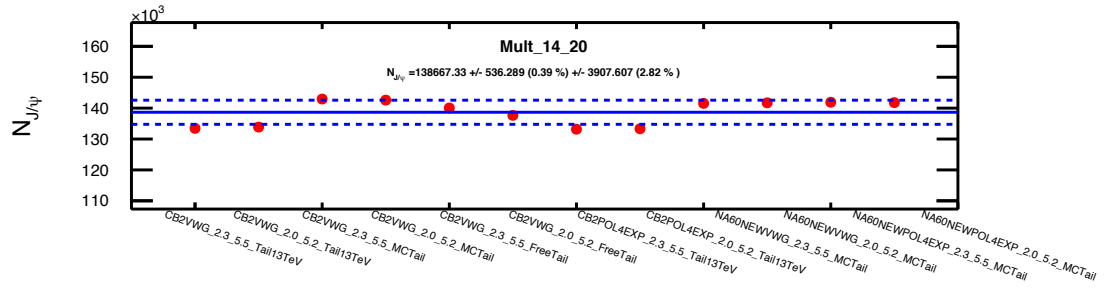


Figure 8.46. (Ref: Maximum) J/ψ yield in different set of tests for the multiplicity bin (15.0, 20.0) [116].

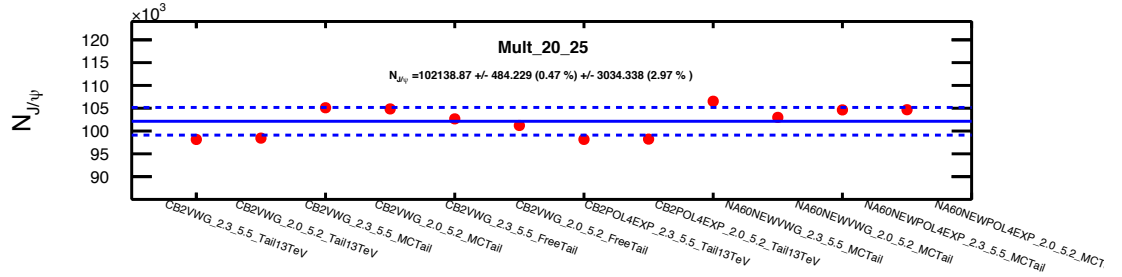


Figure 8.47. (Ref: Maximum) J/ψ yield in different set of tests for the multiplicity bin (21.0, 25.0) [116].

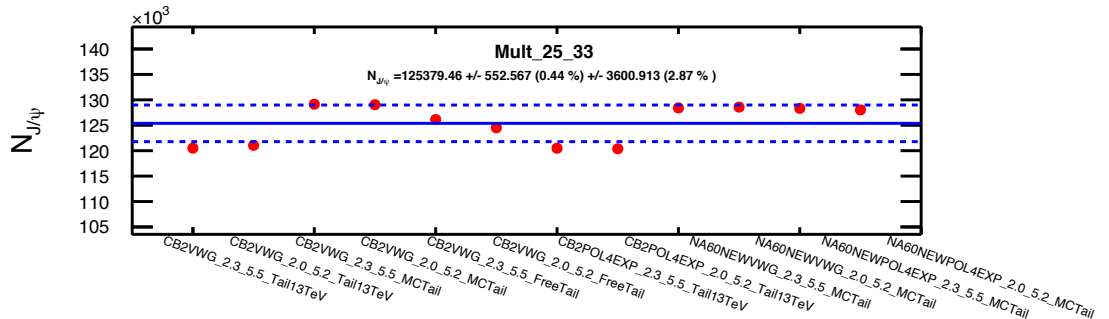


Figure 8.48. (Ref: Maximum) J/ψ yield in different set of tests for the multiplicity bin (26.0, 33.0) [116].

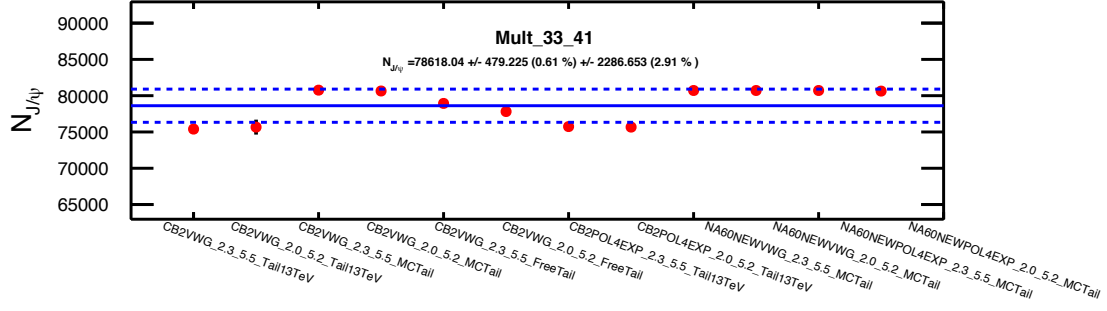


Figure 8.49. (Ref: Maximum) J/ψ yield in different set of tests for the multiplicity bin (34.0, 41.0) [116].

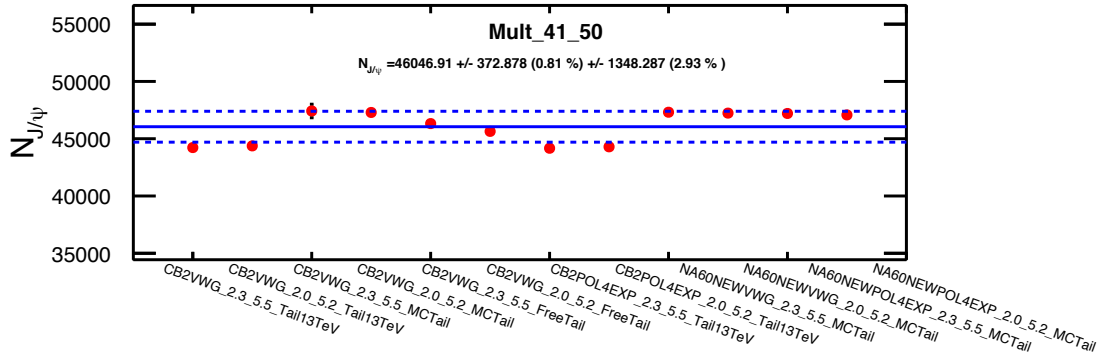


Figure 8.50. (Ref: Maximum) J/ψ yield in different set of tests for the multiplicity bin (42.0, 50.0) [116].

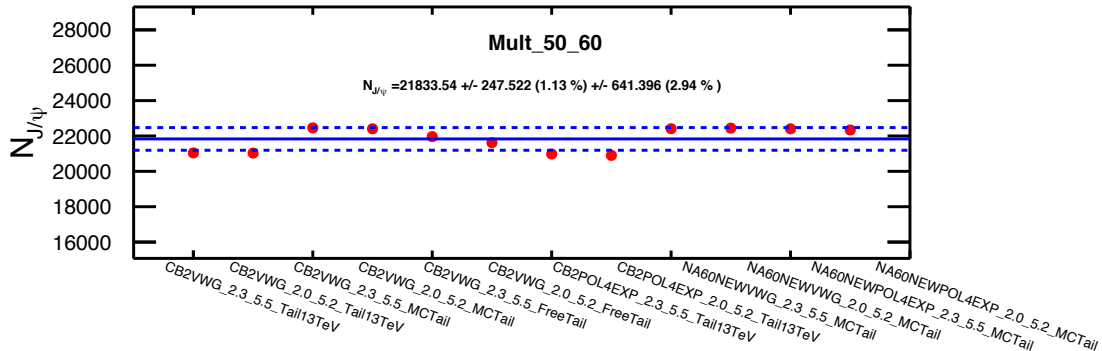


Figure 8.51. (Ref: Maximum) J/ψ yield in different set of tests for the multiplicity bin (51.0, 60.0) [116].

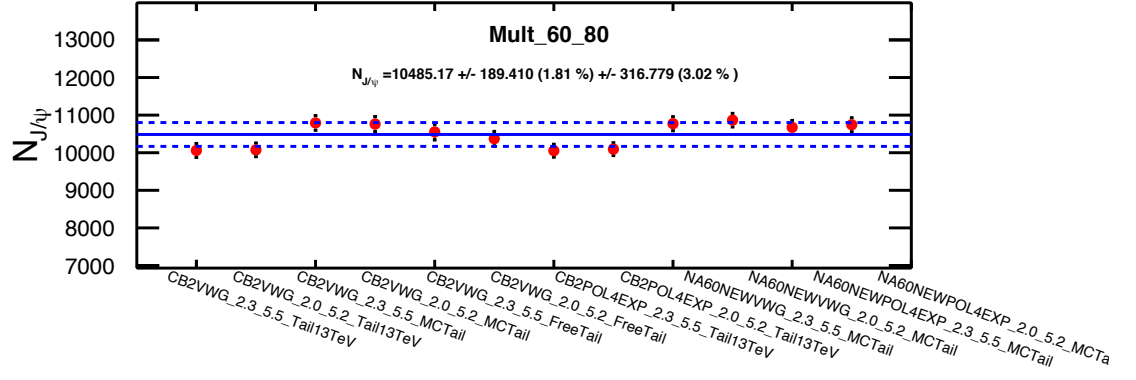


Figure 8.52. (Ref: Maximum) J/ψ yield in different set of tests for the multiplicity bin (61.0, 80.0) [116].

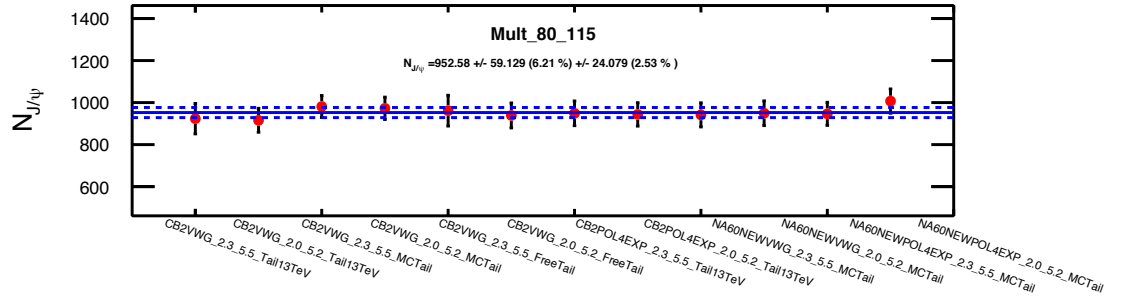


Figure 8.53. (Ref: Maximum) J/ψ yield in different set of tests for the multiplicity bin (81.0, 115.0) [116].

8.13 χ^2/ndf for different tests (Ref: Maximum)

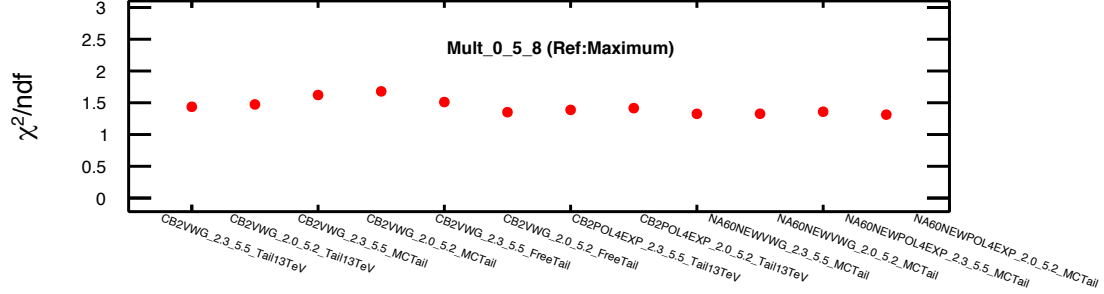


Figure 8.54. (Ref: Maximum) χ^2/ndf in different set of tests for the multiplicity bin (1.0, 8.0) [116].

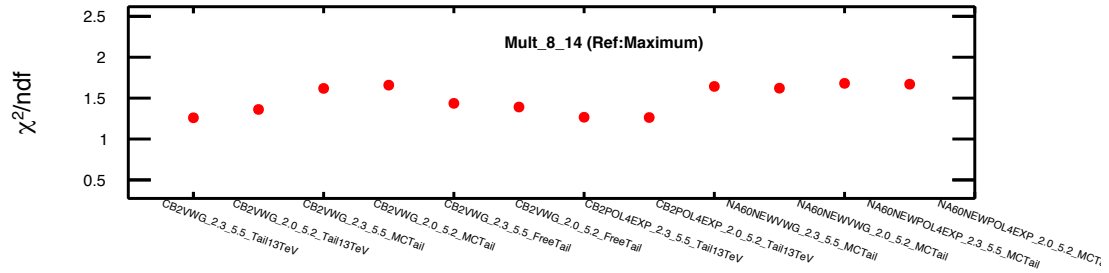


Figure 8.55. (Ref: Maximum) χ^2/ndf in different set of tests for the multiplicity bin (9.0, 14.00) [116].

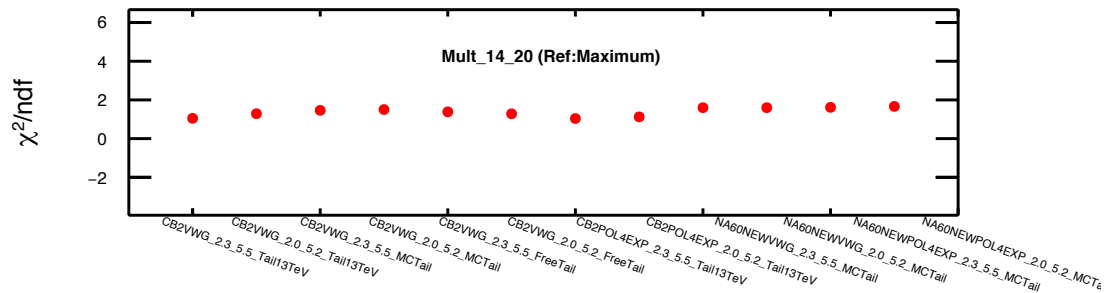


Figure 8.56. (Ref: Maximum) χ^2/ndf in different set of tests for the multiplicity bin (15.0, 20.0) [116].

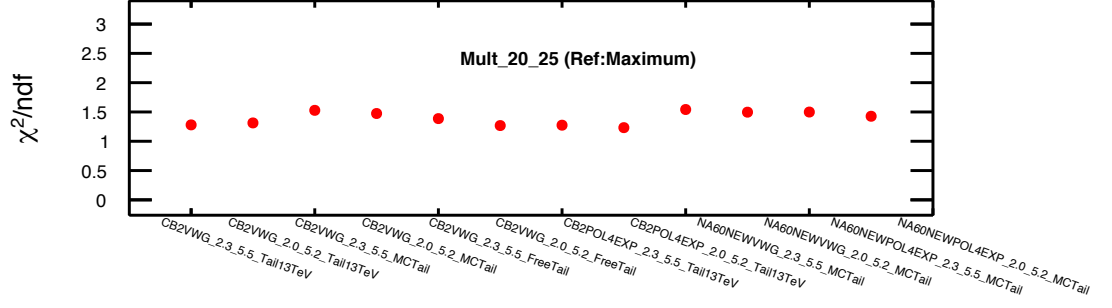


Figure 8.57. (Ref: Maximum) χ^2/ndf in different set of tests for the multiplicity bin (21.0, 25.0) [116].

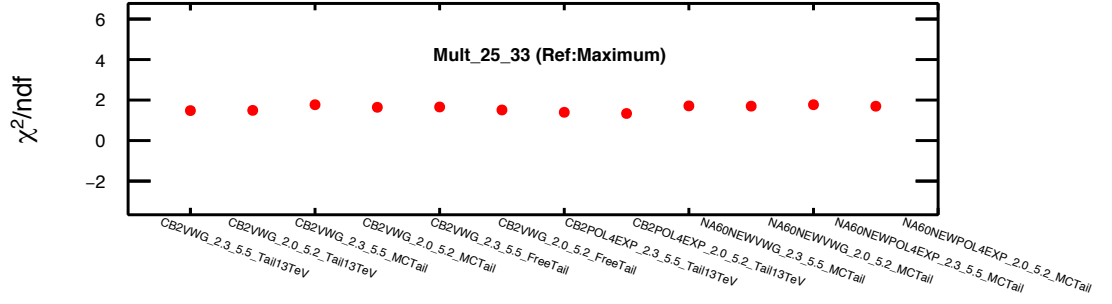


Figure 8.58. (Ref: Maximum) χ^2/ndf in different set of tests for the multiplicity bin (26.0, 33.0) [116].

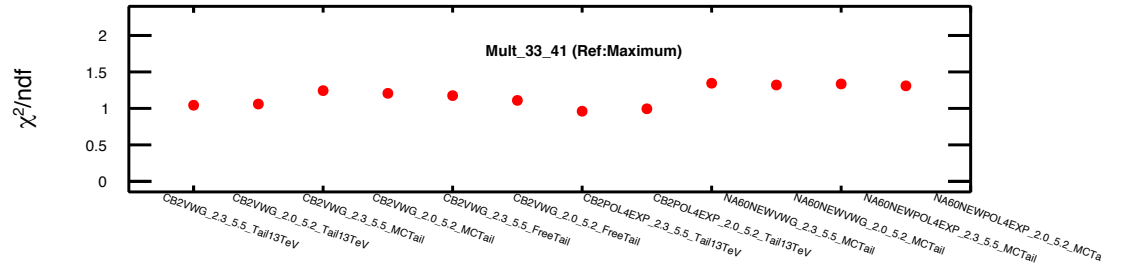


Figure 8.59. (Ref: Maximum) χ^2/ndf in different set of tests for the multiplicity bin (34.0, 41.0) [116].

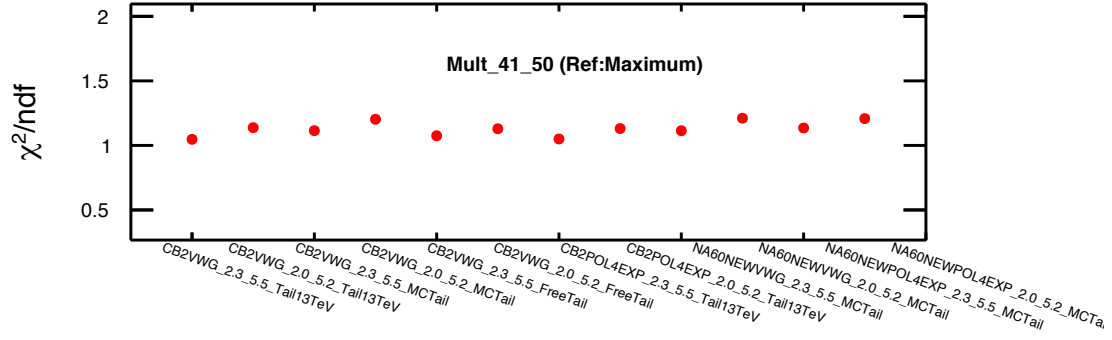


Figure 8.60. (Ref: Maximum) χ^2/ndf in different set of tests for the multiplicity bin (42.0, 50.0) [116].

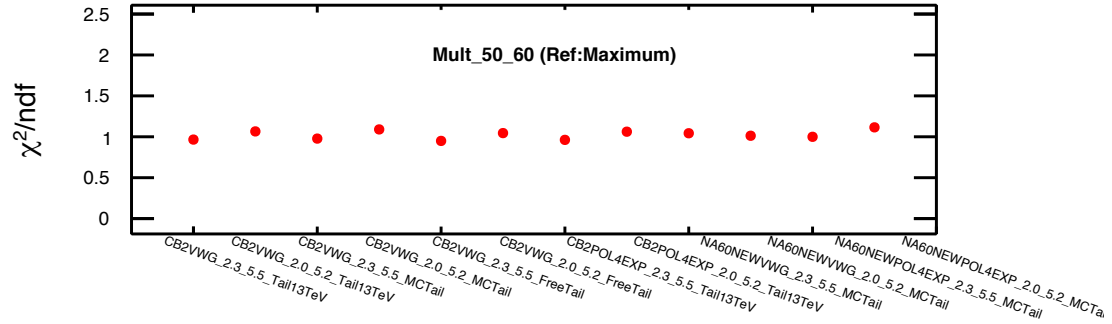


Figure 8.61. (Ref: Maximum) χ^2/ndf in different set of tests for the multiplicity bin (51.0, 60.0) [116].

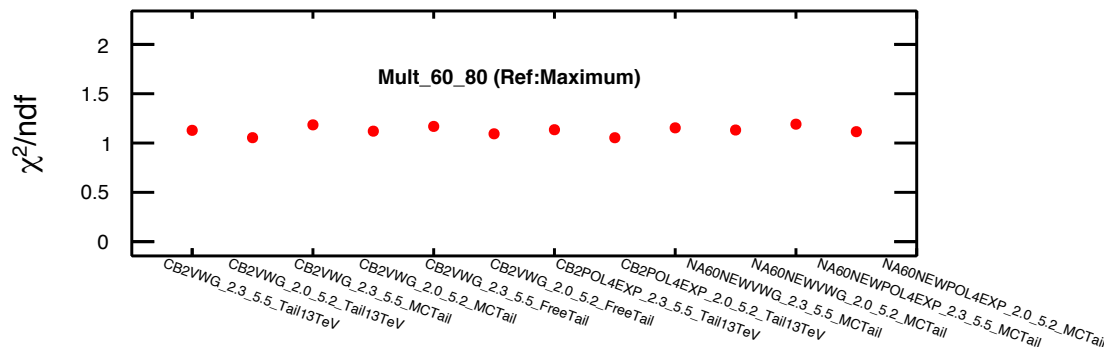


Figure 8.62. (Ref: Maximum) χ^2/ndf in different set of tests for the multiplicity bin (61.0, 80.0) [116].

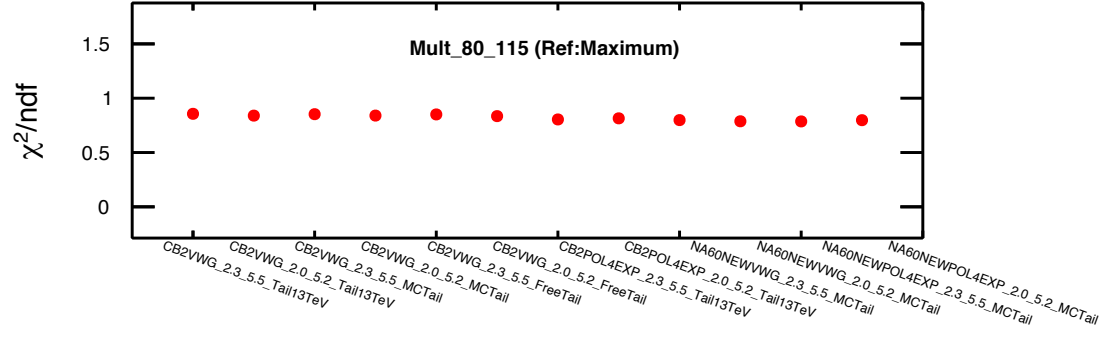


Figure 8.63. (Ref: Maximum) χ^2/ndf in different set of tests for the multiplicity bin (81.0, 115.0) [116].

8.14 $\sigma_{J/\psi}$ for different tests (Ref: Maximum)

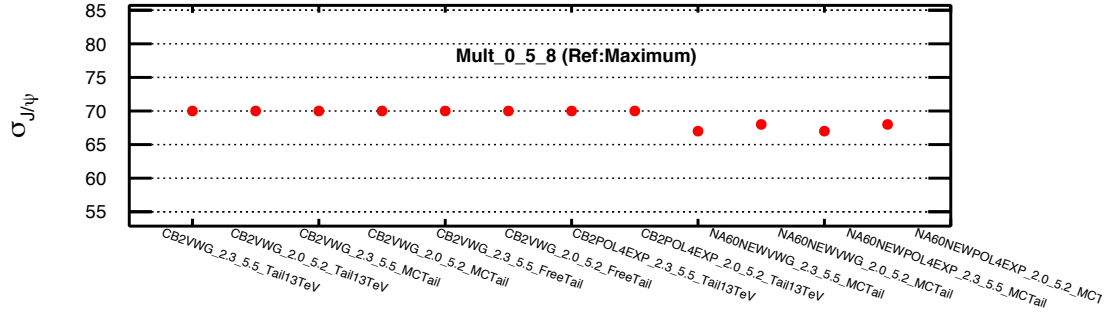


Figure 8.64. (Ref: Maximum) χ^2/ndf in different set of tests for the multiplicity bin (1.0, 8.0) [116].

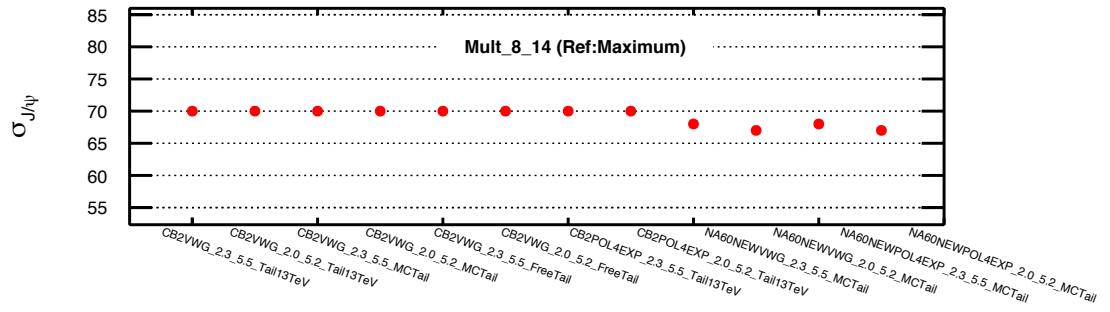


Figure 8.65. (Ref: Maximum) χ^2/ndf in different set of tests for the multiplicity bin (9.0, 14.00) [116].

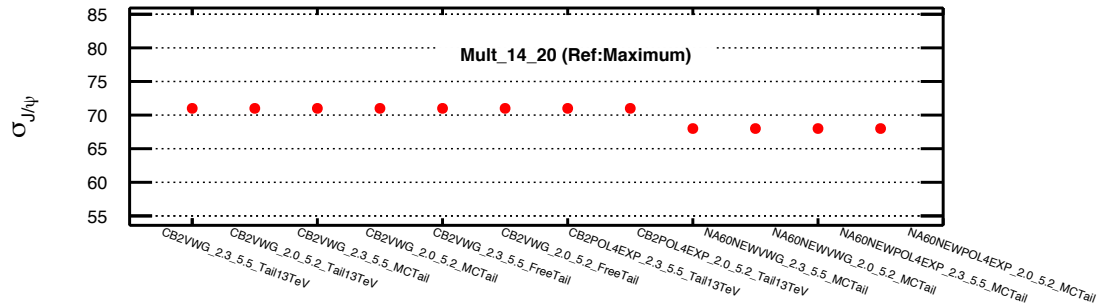


Figure 8.66. (Ref: Maximum) χ^2/ndf in different set of tests for the multiplicity bin (15.0, 20.0) [116].

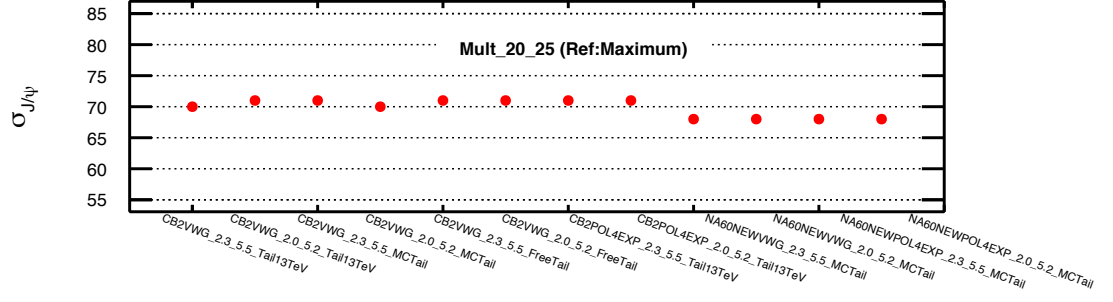


Figure 8.67. (Ref: Maximum) χ^2/ndf in different set of tests for the multiplicity bin (21.0, 25.0) [116].

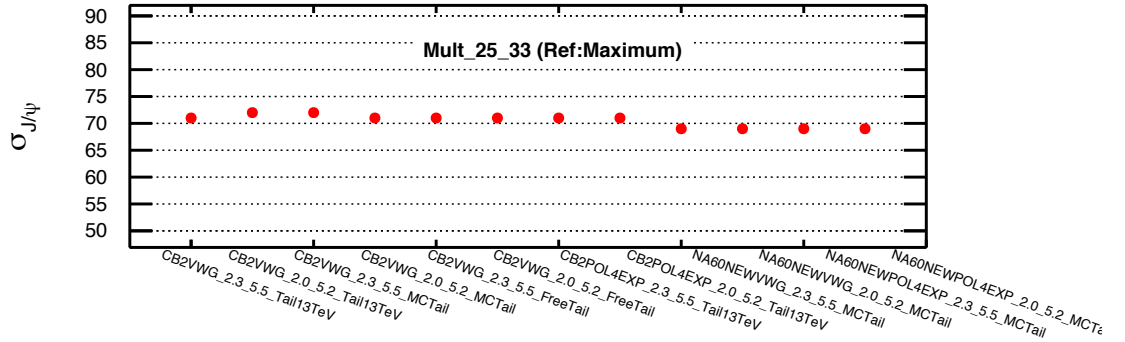


Figure 8.68. (Ref: Maximum) χ^2/ndf in different set of tests for the multiplicity bin (26.0, 33.0) [116].

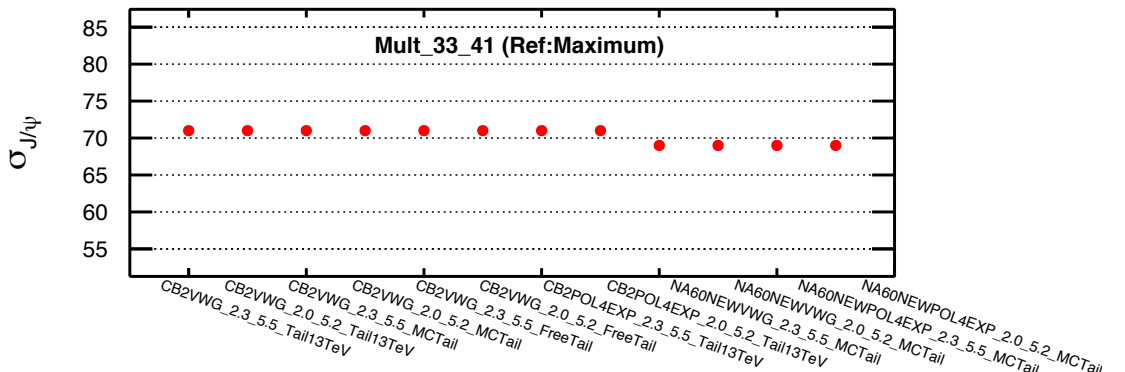


Figure 8.69. (Ref: Maximum) χ^2/ndf in different set of tests for the multiplicity bin (34.0, 41.0) [116].

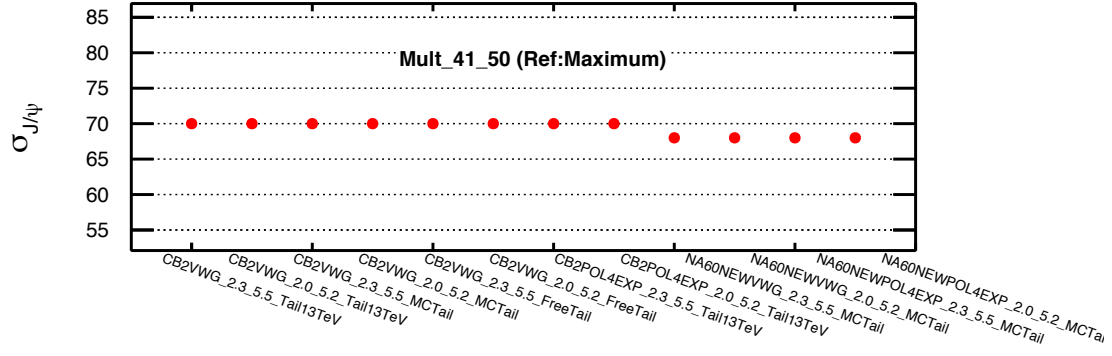


Figure 8.70. (Ref: Maximum) χ^2/ndf in different set of tests for the multiplicity bin (42.0, 50.0) [116].

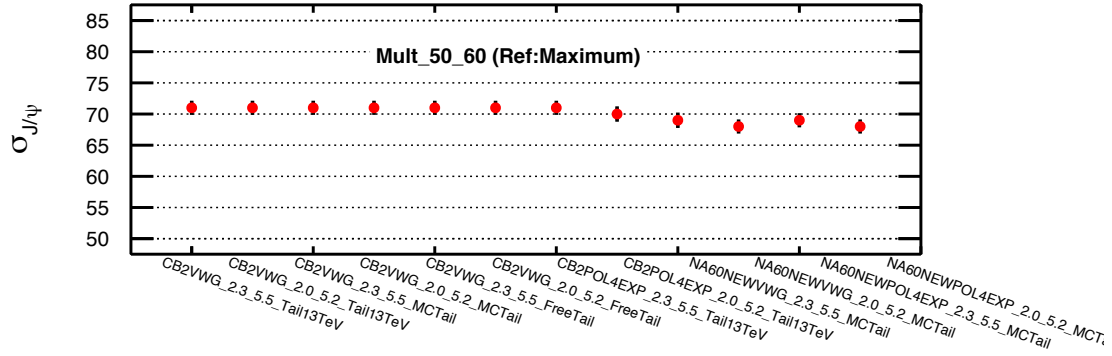


Figure 8.71. (Ref: Maximum) χ^2/ndf in different set of tests for the multiplicity bin (51.0, 60.0) [116].

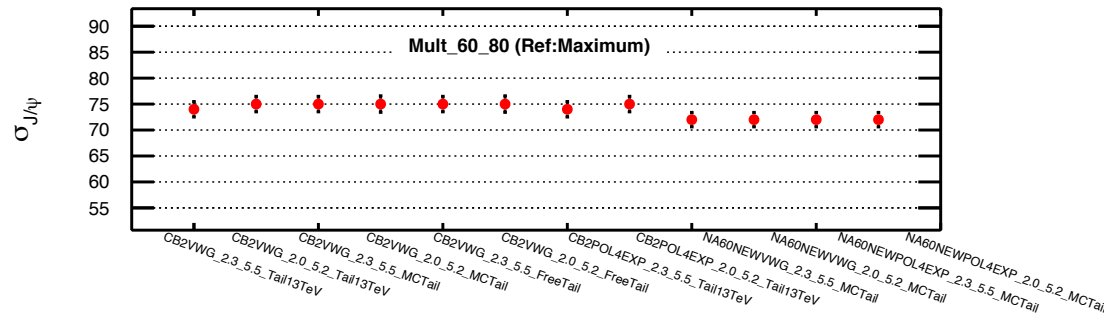


Figure 8.72. (Ref: Maximum) χ^2/ndf in different set of tests for the multiplicity bin (61.0, 80.0) [116].

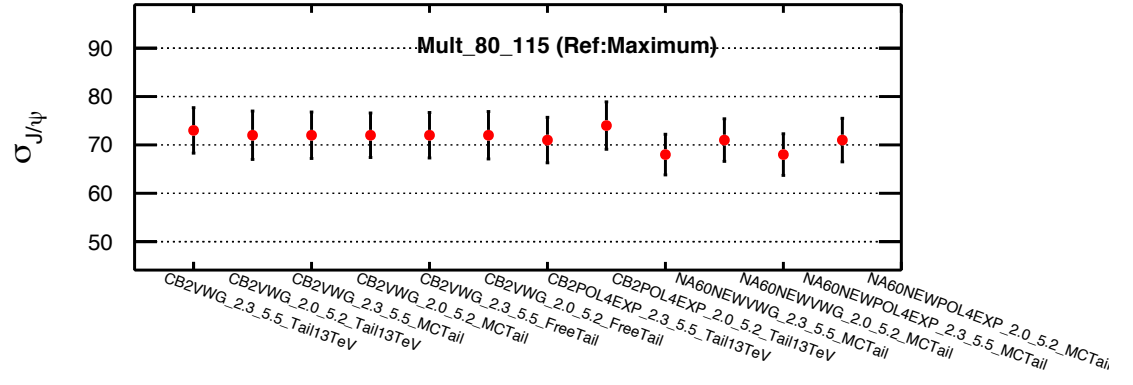


Figure 8.73. (Ref: Maximum) χ^2/ndf in different set of tests for the multiplicity bin (81.0, 115.0) [116].

8.15 Signal systematics Plots (Ref: Minimum)

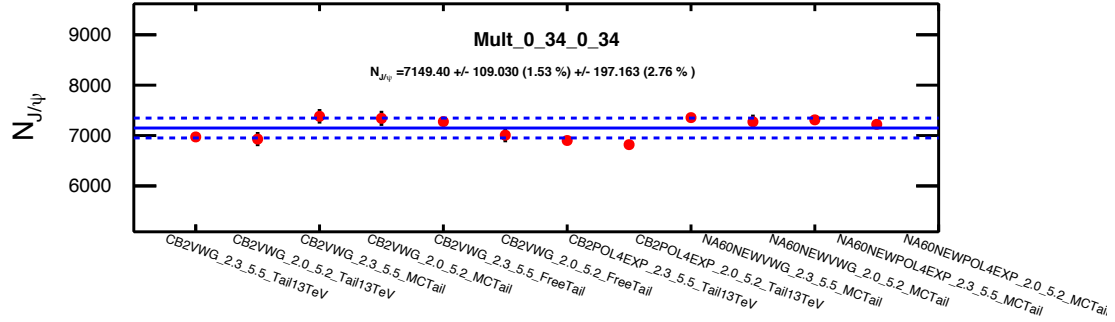


Figure 8.74. (Ref: Minimum) J/ψ yield in different set of tests for the multiplicity bin $(-0.34, 0.34)$ [116].

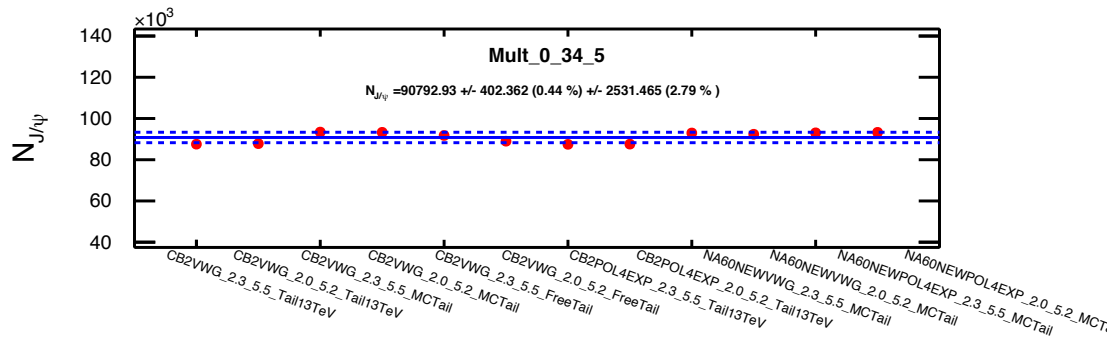


Figure 8.75. (Ref: Minimum) J/ψ yield in different set of tests for the multiplicity bin $(1.0, 5.0)$ [116].

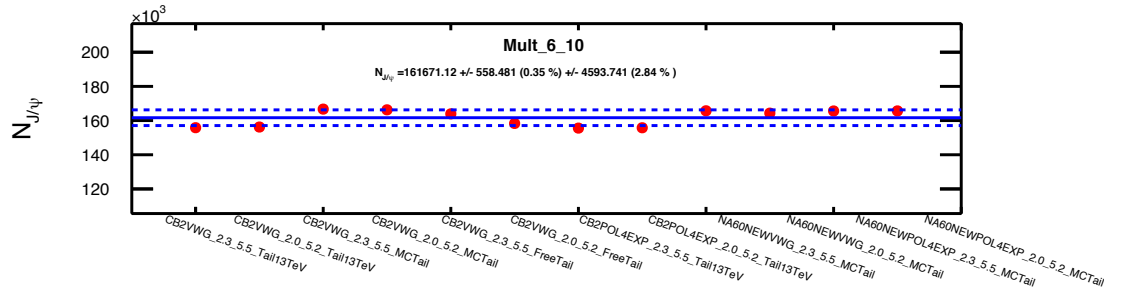


Figure 8.76. (Ref: Minimum) J/ψ yield in different set of tests for the multiplicity bin (6.0, 10.00) [116].

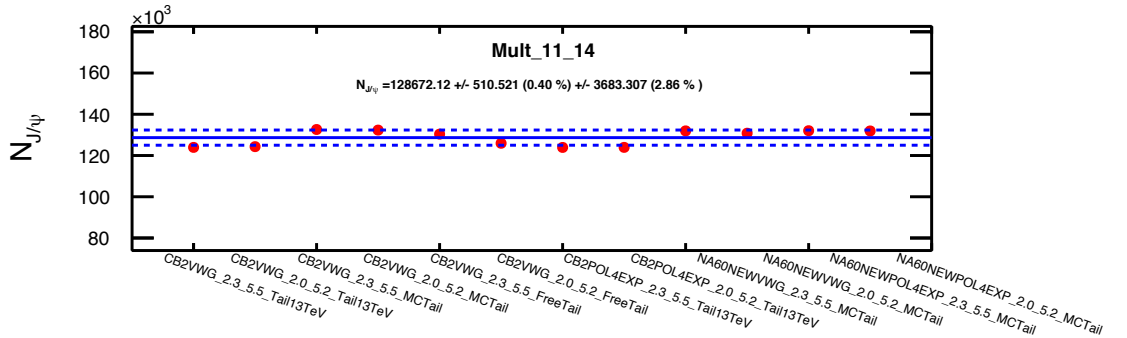


Figure 8.77. (Ref: Minimum) J/ψ yield in different set of tests for the multiplicity bin (11.0, 14.0) [116].

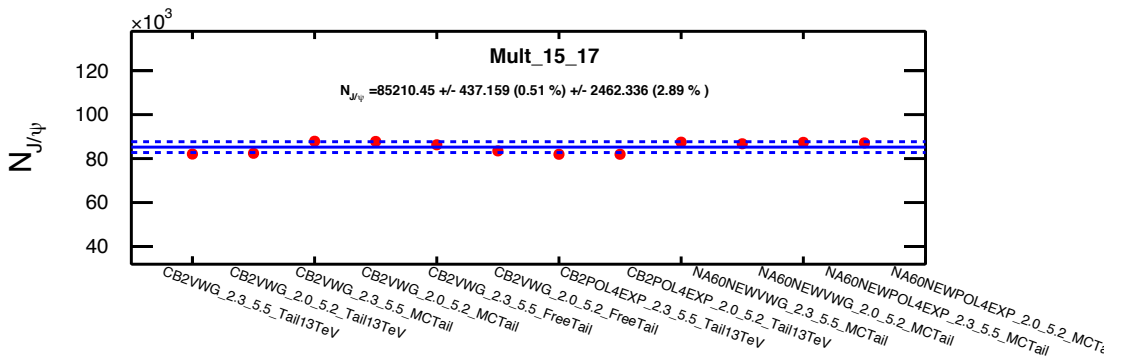


Figure 8.78. (Ref: Minimum) J/ψ yield in different set of tests for the multiplicity bin (15.0, 17.0) [116].

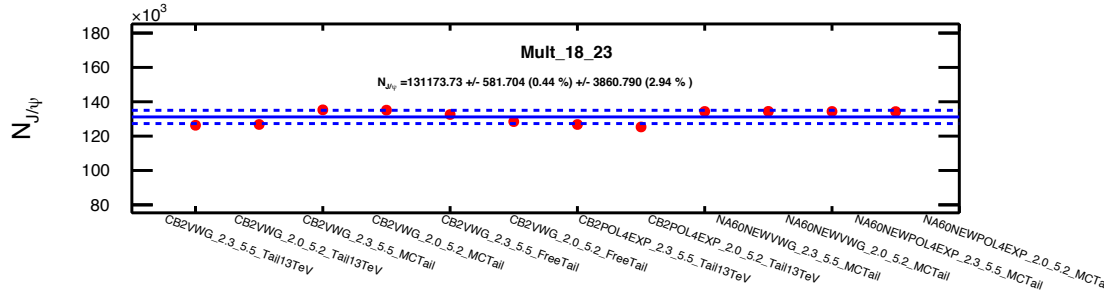


Figure 8.79. (Ref: Minimum) J/ψ yield in different set of tests for the multiplicity bin (18.0, 23.0) [116].

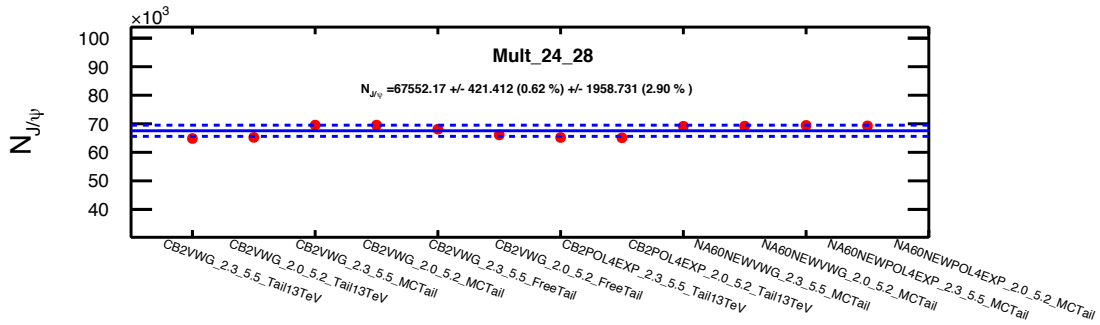


Figure 8.80. (Ref: Minimum) J/ψ yield in different set of tests for the multiplicity bin (24.0, 28.0) [116].

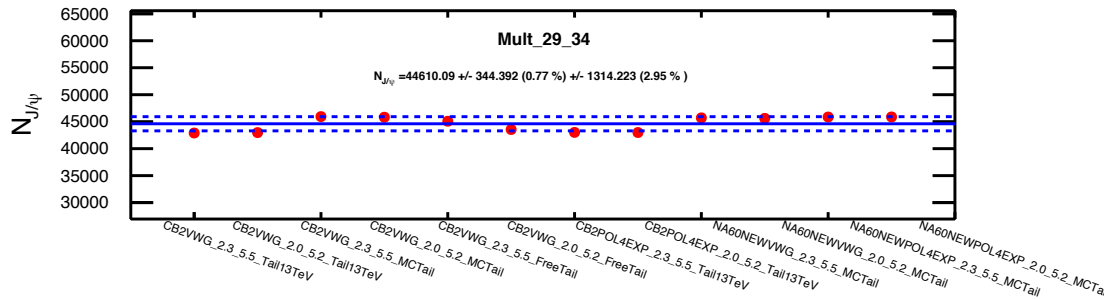


Figure 8.81. (Ref: Minimum) J/ψ yield in different set of tests for the multiplicity bin (29.0, 34.0) [116].

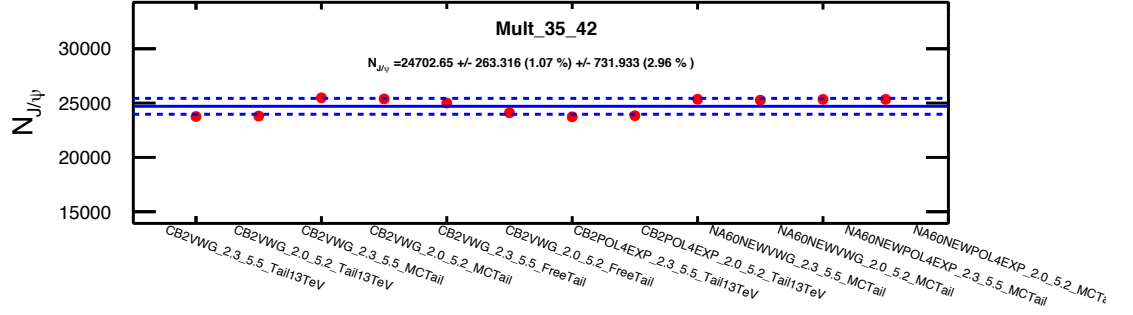


Figure 8.82. (Ref: Minimum) J/ψ yield in different set of tests for the multiplicity bin (35.0, 42.0) [116].

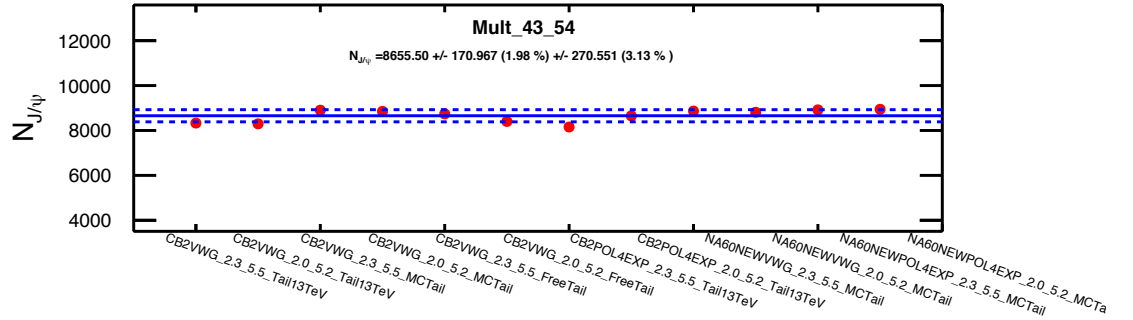


Figure 8.83. (Ref: Minimum) J/ψ yield in different set of tests for the multiplicity bin (43.0, 54.0) [116].

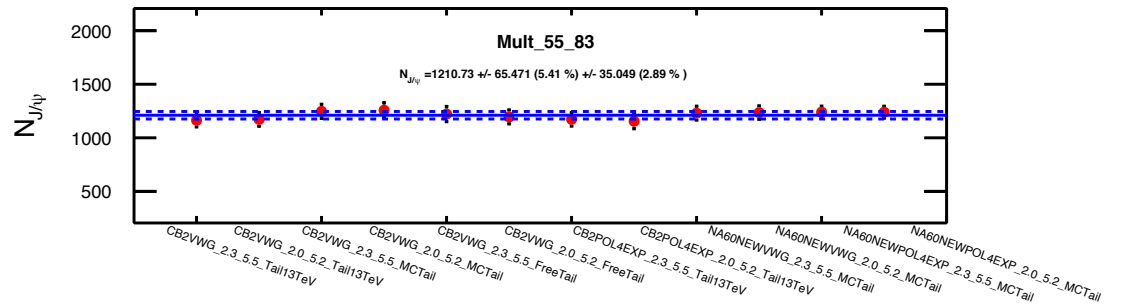


Figure 8.84. (Ref: Minimum) J/ψ yield in different set of tests for the multiplicity bin (55.0, 83.0) [116].

8.16 χ^2/ndf for different tests (Ref: Minimum)

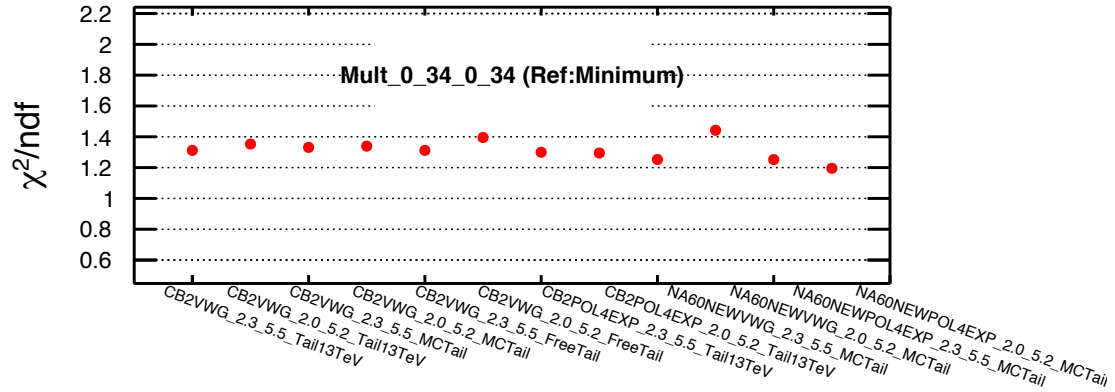


Figure 8.85. (Ref: Minimum) χ^2/ndf in different set of tests for the multiplicity bin $(-0.34, 0.34)$ [116].

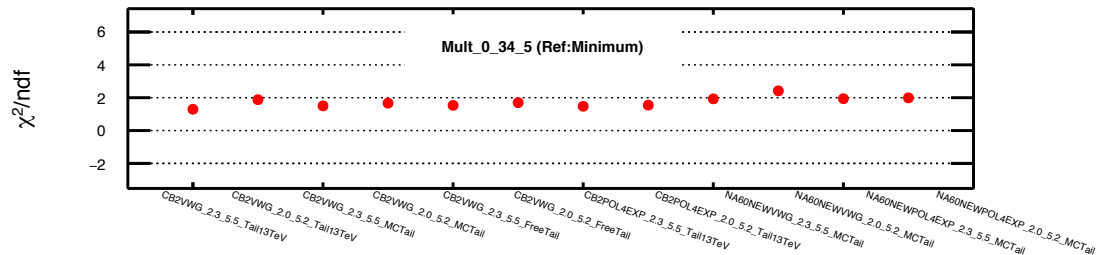


Figure 8.86. (Ref: Minimum) χ^2/ndf in different set of tests for the multiplicity bin $(0.34, 5.0)$ [116].

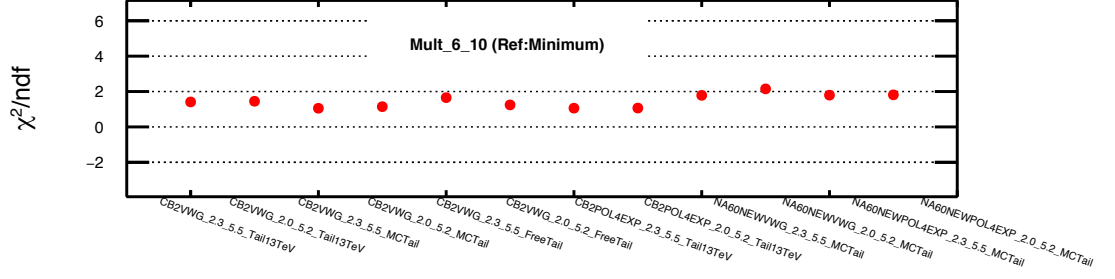


Figure 8.87. (Ref: Minimum) χ^2/ndf in different set of tests for the multiplicity bin (6.0, 10.00) [116].

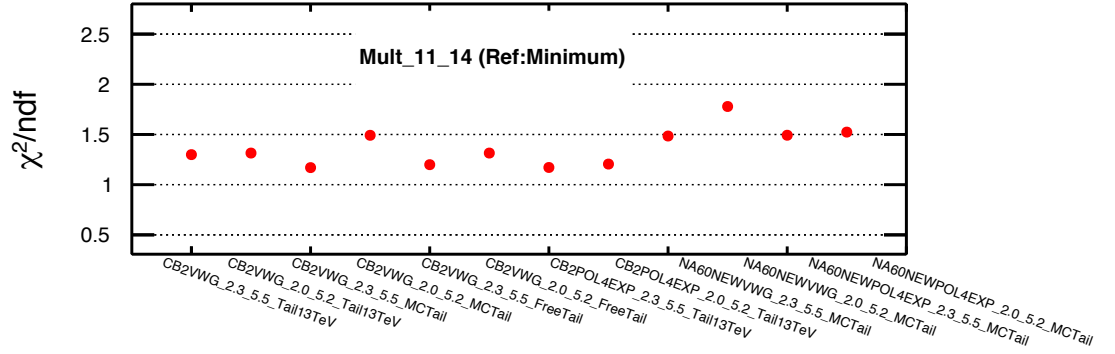


Figure 8.88. (Ref: Minimum) χ^2/ndf in different set of tests for the multiplicity bin (11.0, 14.0) [116].

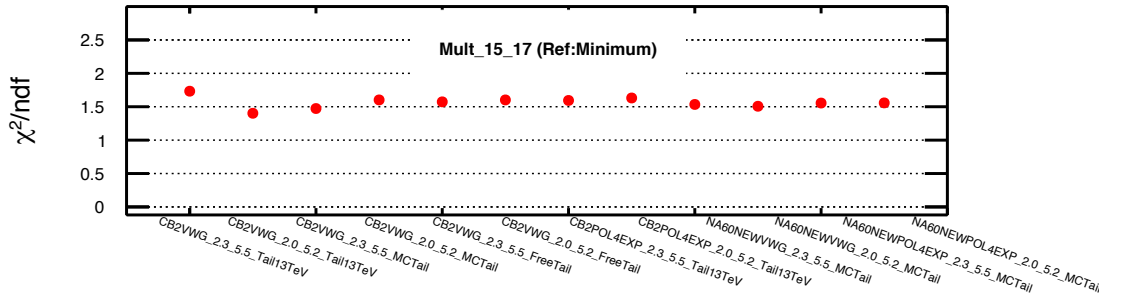


Figure 8.89. (Ref: Minimum) χ^2/ndf in different set of tests for the multiplicity bin (15.0, 17.0) [116].

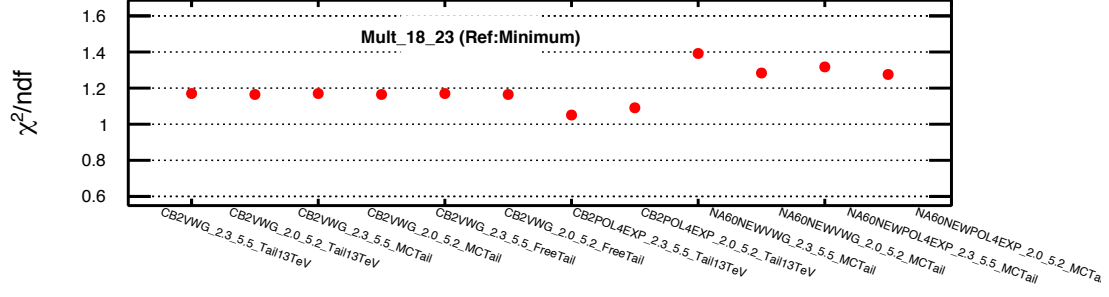


Figure 8.90. (Ref: Minimum) χ^2/ndf in different set of tests for the multiplicity bin (18.0, 23.0) [116].

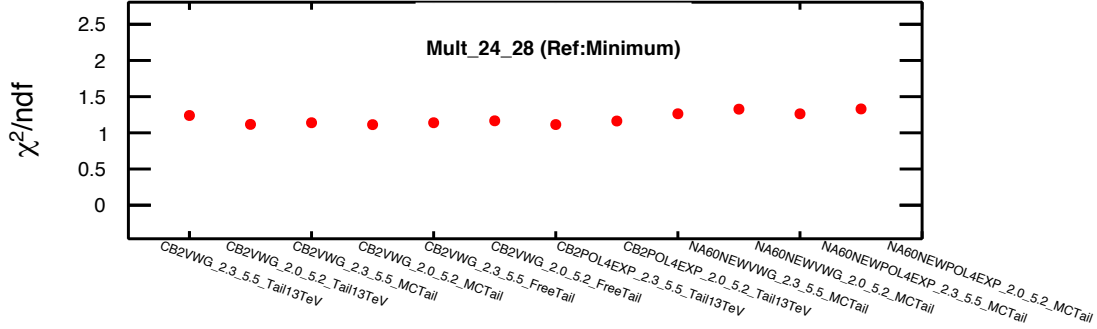


Figure 8.91. (Ref: Minimum) χ^2/ndf in different set of tests for the multiplicity bin (24.0, 28.0) [116].

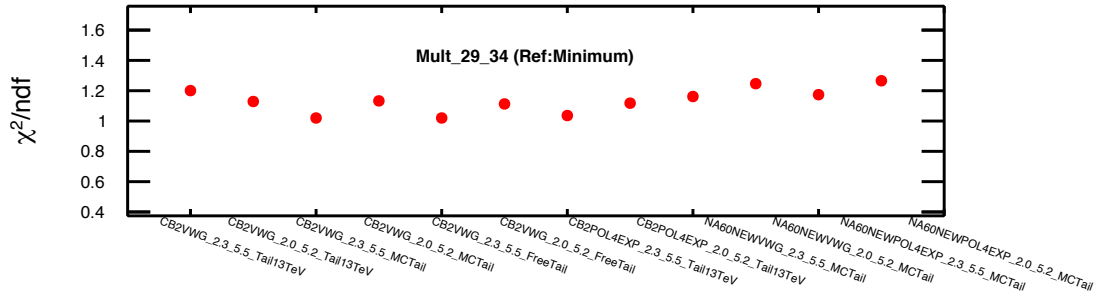


Figure 8.92. (Ref: Minimum) χ^2/ndf in different set of tests for the multiplicity bin (29.0, 34.0) [116].

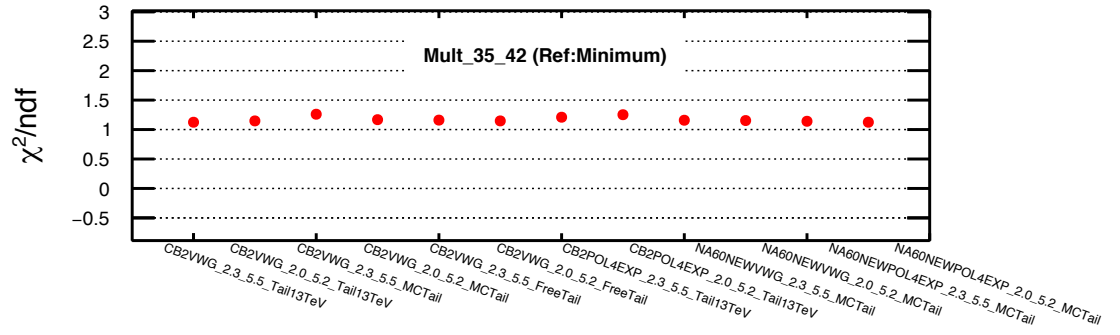


Figure 8.93. (Ref: Minimum) χ^2/ndf in different set of tests for the multiplicity bin (35.0, 42.0) [116].

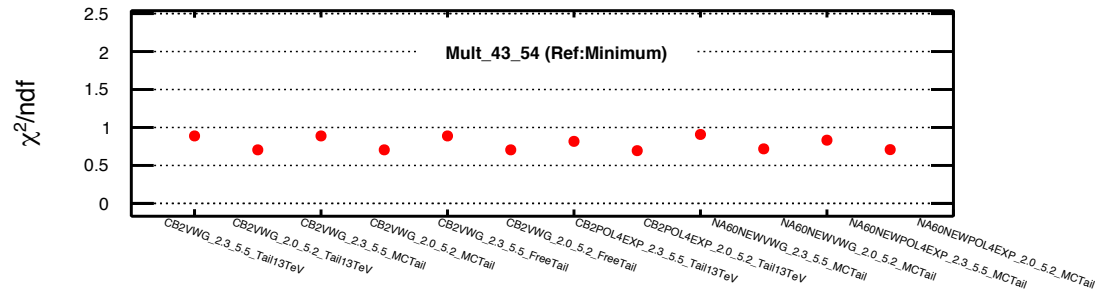


Figure 8.94. (Ref: Minimum) χ^2/ndf in different set of tests for the multiplicity bin (43.0, 54.0) [116].

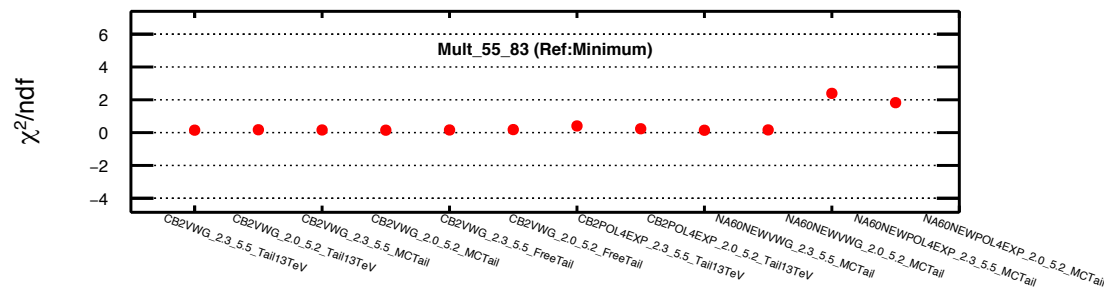


Figure 8.95. (Ref: Minimum) χ^2/ndf in different set of tests for the multiplicity bin (55.0, 83.0) [116].

8.17 $\sigma_{J/\psi}$ for different tests (Ref: Minimum)

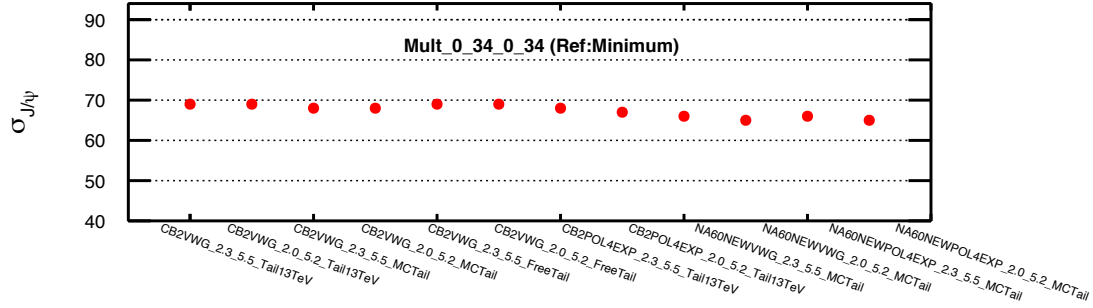


Figure 8.96. (Ref: Minimum) χ^2/ndf in different set of tests for the multiplicity bin $(-0.34, 0.34)$ [116].

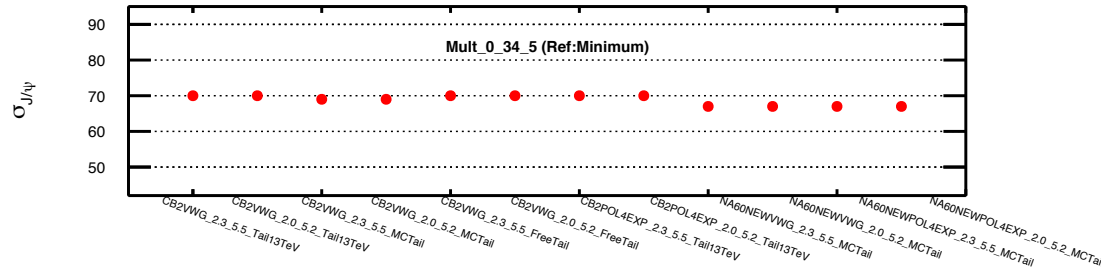


Figure 8.97. (Ref: Minimum) χ^2/ndf in different set of tests for the multiplicity bin $(0.34, 5.00)$ [116].

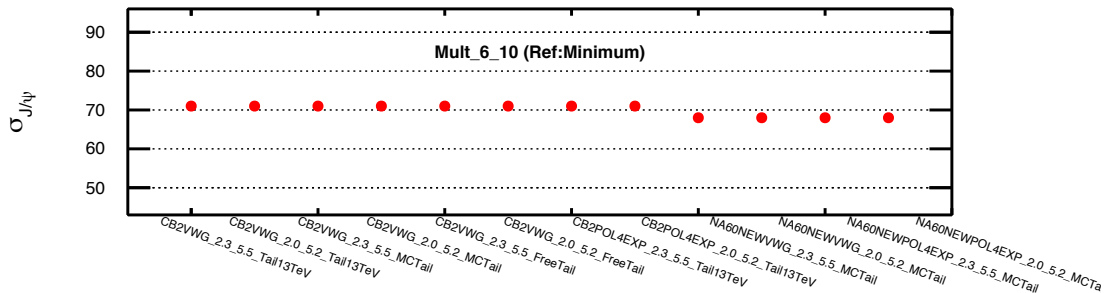


Figure 8.98. (Ref: Minimum) χ^2/ndf in different set of tests for the multiplicity bin $(6.0, 10.0)$ [116].

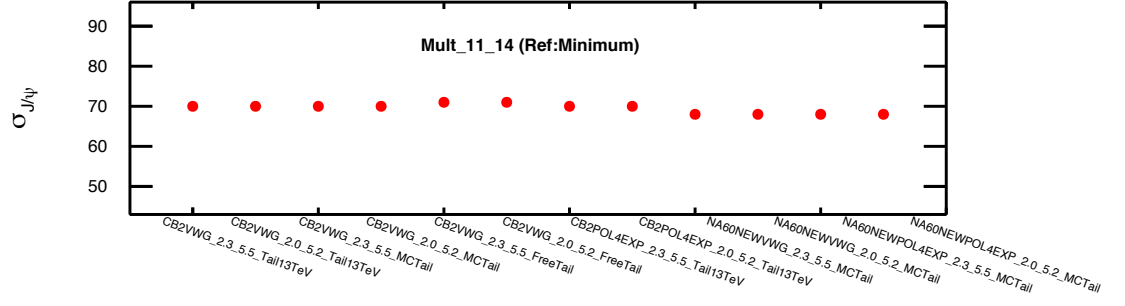


Figure 8.99. (Ref: Minimum) χ^2/ndf in different set of tests for the multiplicity bin (11.0, 14.0) [116].

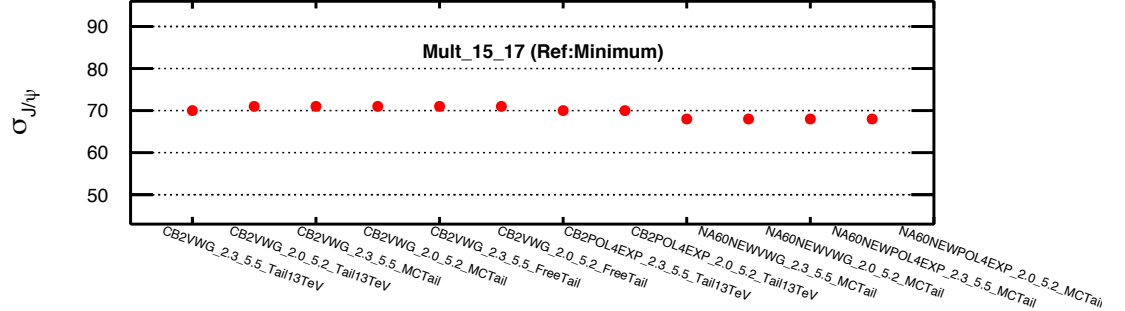


Figure 8.100. (Ref: Minimum) χ^2/ndf in different set of tests for the multiplicity bin (15.0, 17.0) [116].

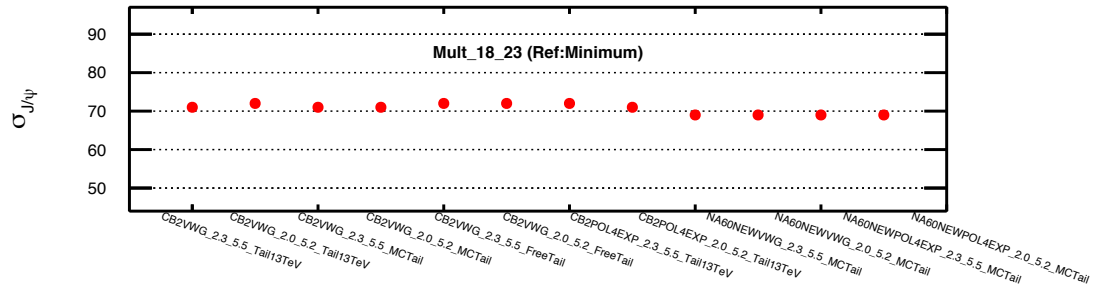


Figure 8.101. (Ref: Minimum) χ^2/ndf in different set of tests for the multiplicity bin (18.0, 23.0) [116].

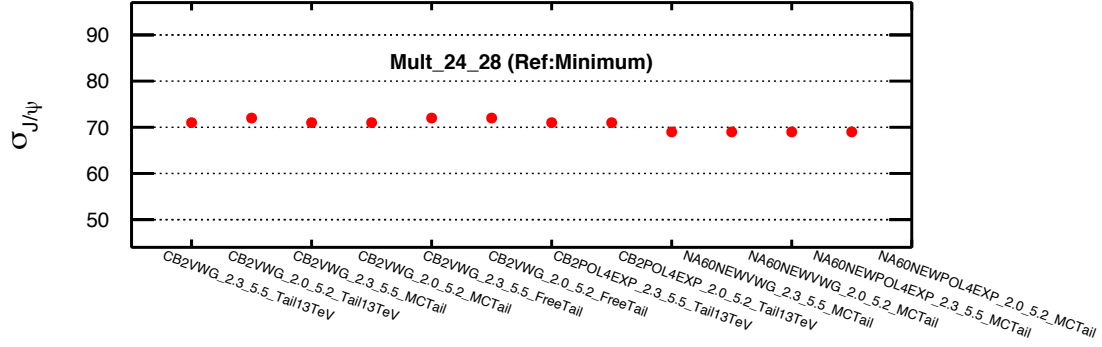


Figure 8.102. (Ref: Minimum) χ^2/ndf in different set of tests for the multiplicity bin (24.0, 28.0) [116].

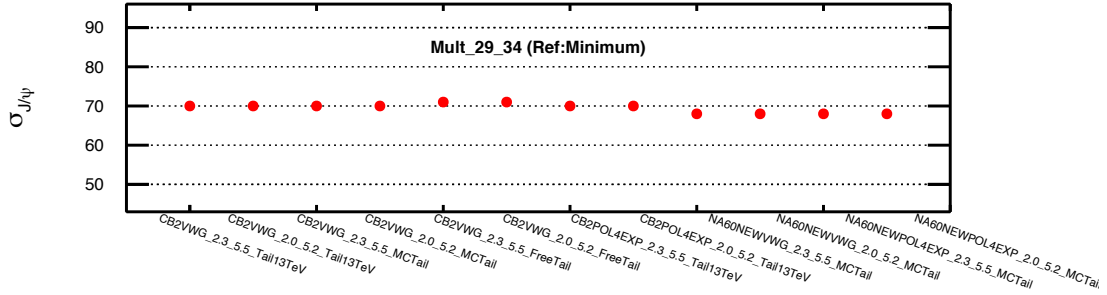


Figure 8.103. (Ref: Minimum) χ^2/ndf in different set of tests for the multiplicity bin (29.0, 34.0) [116].

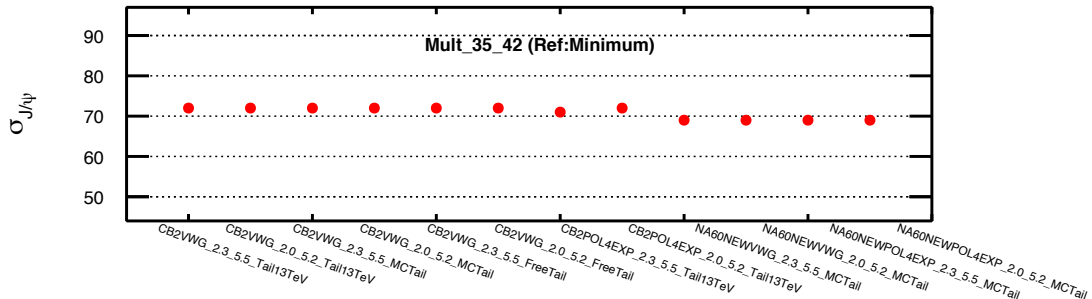


Figure 8.104. (Ref: Minimum) χ^2/ndf in different set of tests for the multiplicity bin (35.0, 42.0) [116].

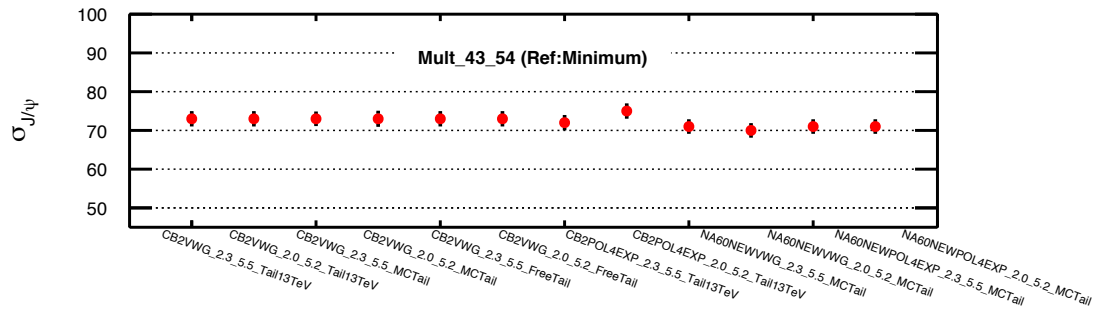


Figure 8.105. (Ref: Minimum) χ^2/ndf in different set of tests for the multiplicity bin (43.0, 54.0) [116].

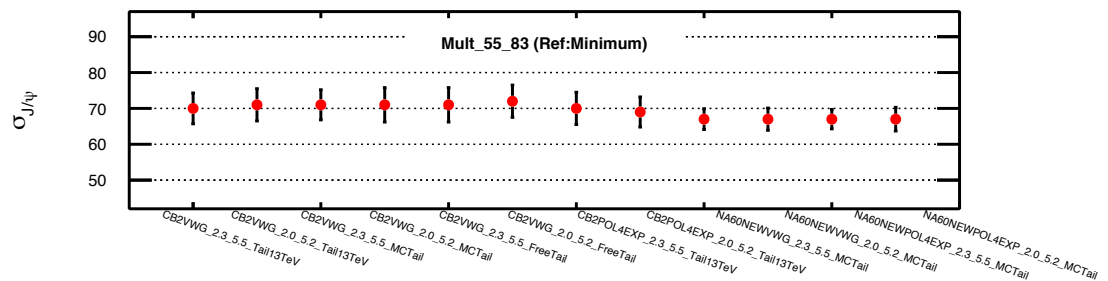


Figure 8.106. (Ref: Minimum) χ^2/ndf in different set of tests for the multiplicity bin (55.0, 83.0) [116].

8.18 Comparison study of Variation of the dimuon $\langle p_T \rangle$ as a function of the invariant mass between 2015 and 2016 data set

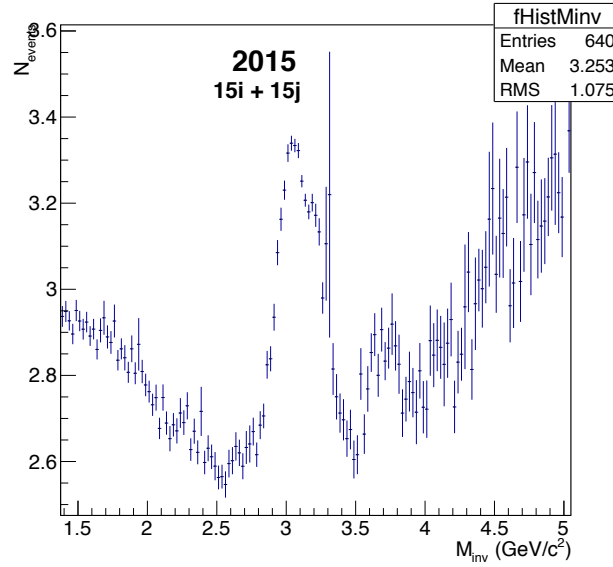


Figure 8.107. $\langle p_T^{\mu^+\mu^-} \rangle$ as a function of $M_{\mu^+\mu^-}$ for 2015 period [116].

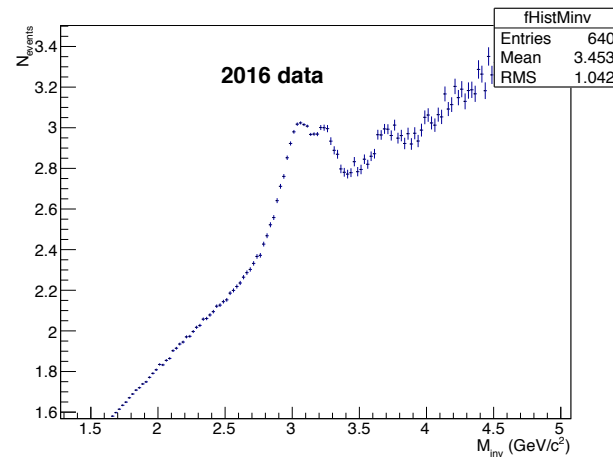


Figure 8.108. $\langle p_T^{\mu^+\mu^-} \rangle$ as a function of $M_{\mu^+\mu^-}$ for 2016 period [116].

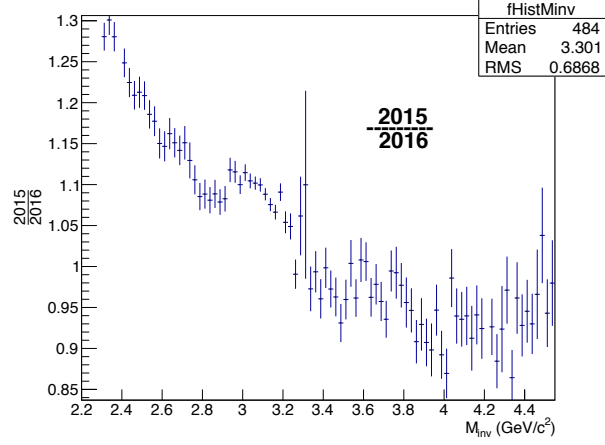


Figure 8.109. Ratio between 2015 and 2016 data [116].

8.19 Fitting to invariant mass spectra in p_T bins

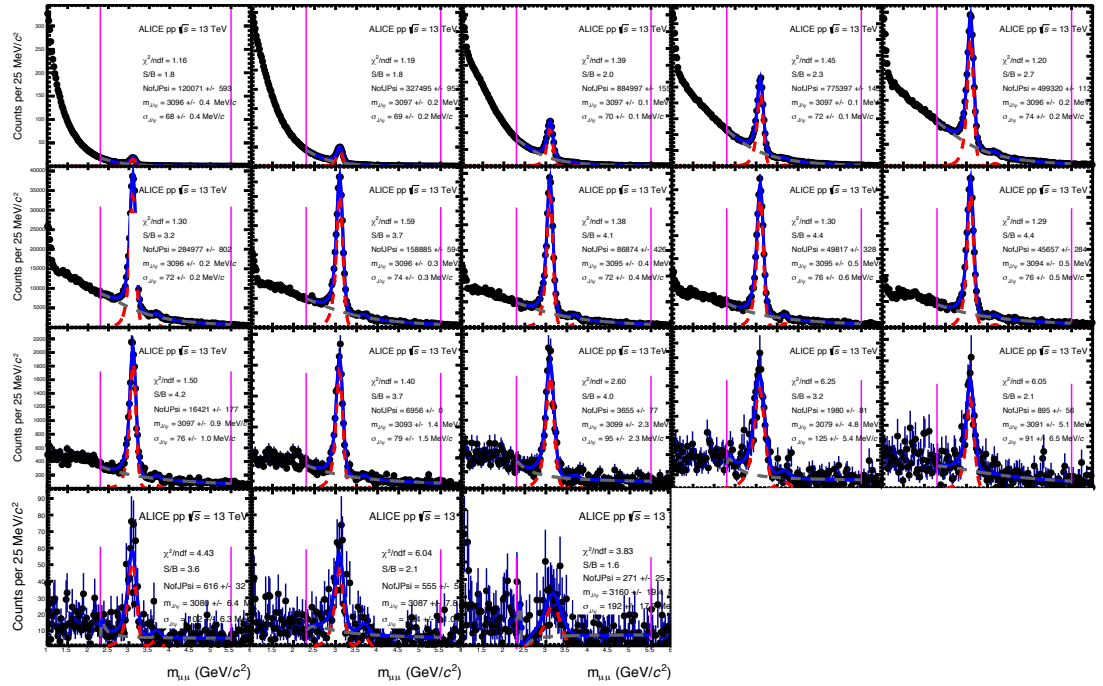


Figure 8.110. Example of fitting to invariant mass spectra in p_T bins for the combination of fit “CB2+VWG” [116].

8.20 Systematics plots to extract J/ψ in p_T bins

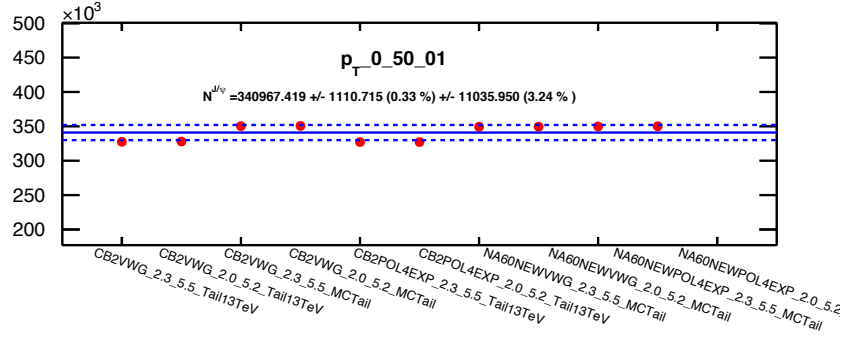


Figure 8.111. J/ψ yield in different set of tests for the p_T bin (0.5, 1.0) GeV/c [116].

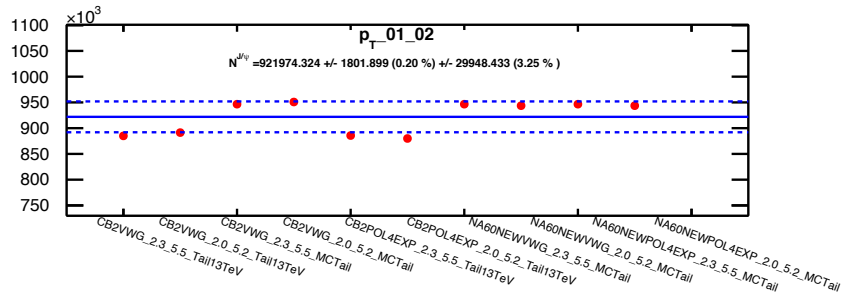


Figure 8.112. J/ψ yield in different set of tests for the p_T bin (1.0, 2.0) GeV/c [116].

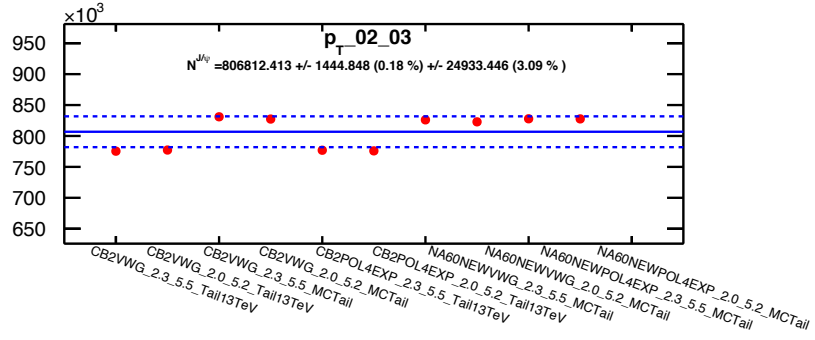


Figure 8.113. J/ψ yield in different set of tests for the p_T bin (2.0, 3.0) GeV/c [116].

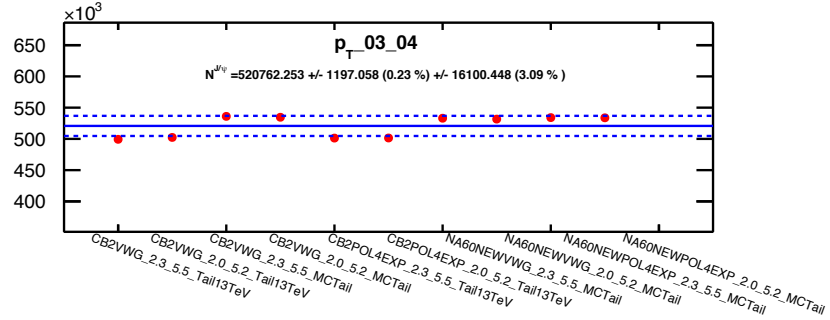


Figure 8.114. J/ψ yield in different set of tests for the p_T bin (3.0, 4.0) GeV/c [116].

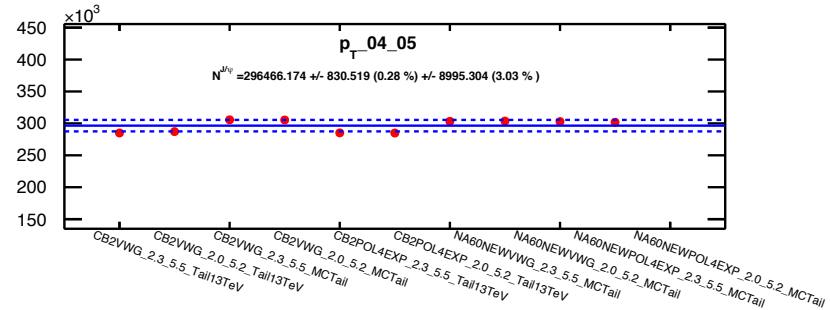


Figure 8.115. J/ψ yield in different set of tests for the p_T bin (4.0, 5.0) GeV/c [116].

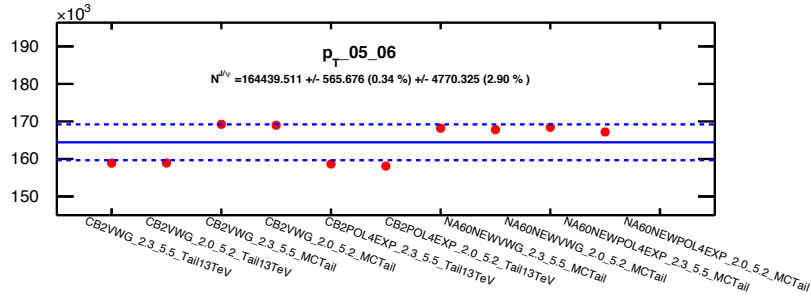


Figure 8.116. J/ψ yield in different set of tests for the p_T bin (5.0, 6.0) GeV/c [116].

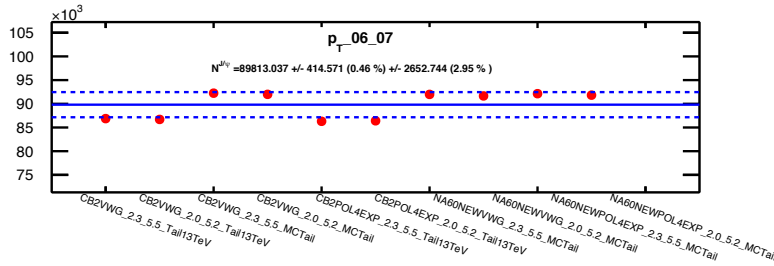


Figure 8.117. J/ψ yield in different set of tests for the p_T bin (6.0, 7.0) GeV/c [116].

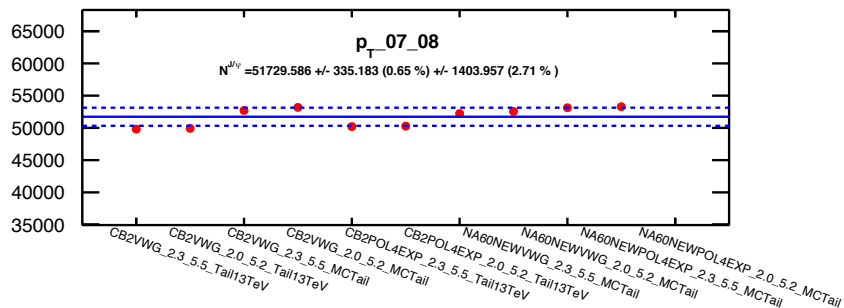


Figure 8.118. J/ψ yield in different set of tests for the p_T bin (7.0, 8.0) GeV/c [116].

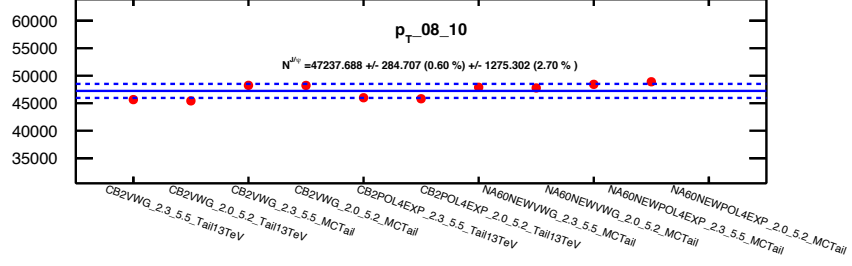


Figure 8.119. J/ψ yield in different set of tests for the p_T bin (8.0, 10.0) GeV/c [116].

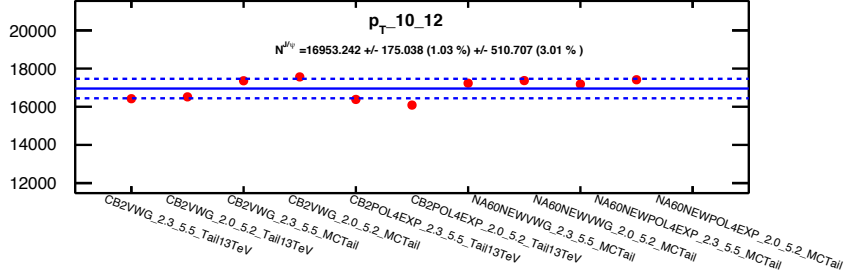


Figure 8.120. J/ψ yield in different set of tests for the p_T bin (10.0, 12.0) GeV/c [116].

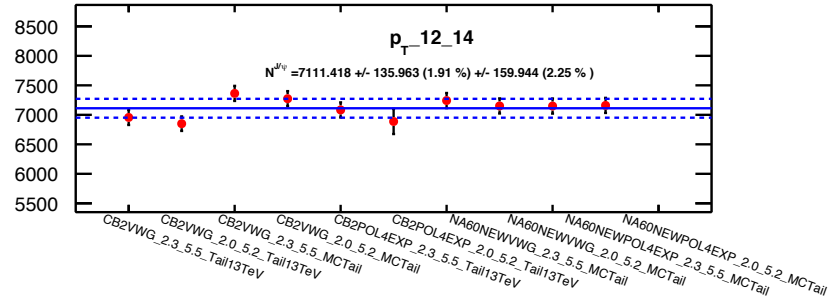


Figure 8.121. J/ψ yield in different set of tests for the p_T bin (12.0, 14.0) GeV/c [116].

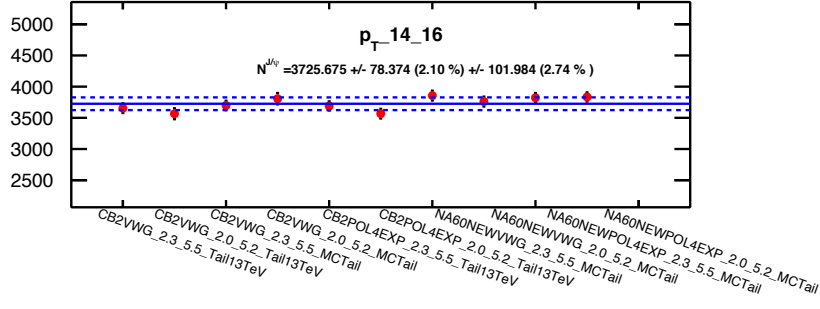


Figure 8.122. J/ψ yield in different set of tests for the p_T bin (14.0, 16.0) GeV/c [116].

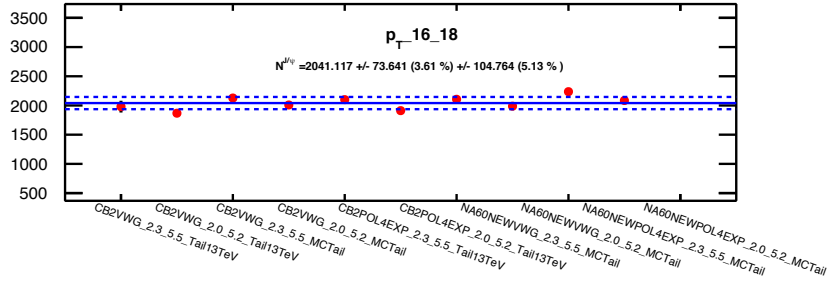


Figure 8.123. J/ψ yield in different set of tests for the p_T bin (16.0, 18.0) GeV/c [116].

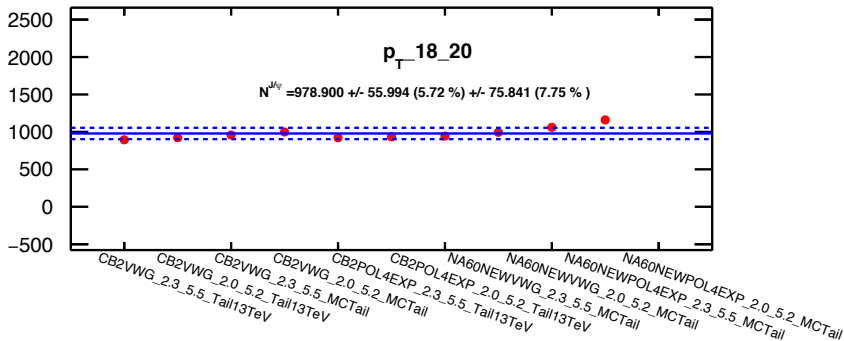


Figure 8.124. J/ψ yield in different set of tests for the p_T bin (18.0, 20.0) GeV/c [116].

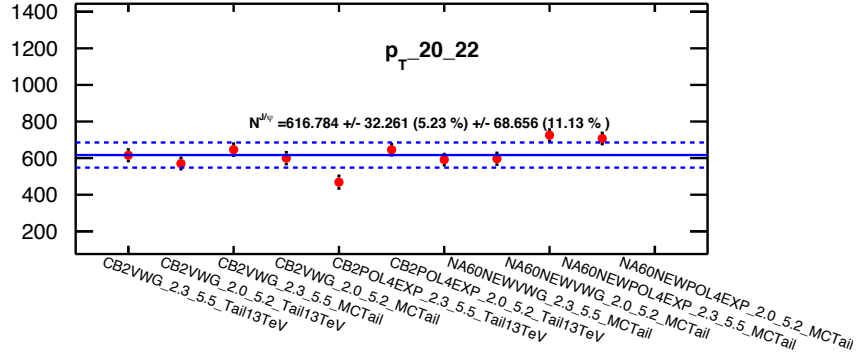


Figure 8.125. J/ψ yield in different set of tests for the p_T bin (20.0, 22.0) GeV/c [116].

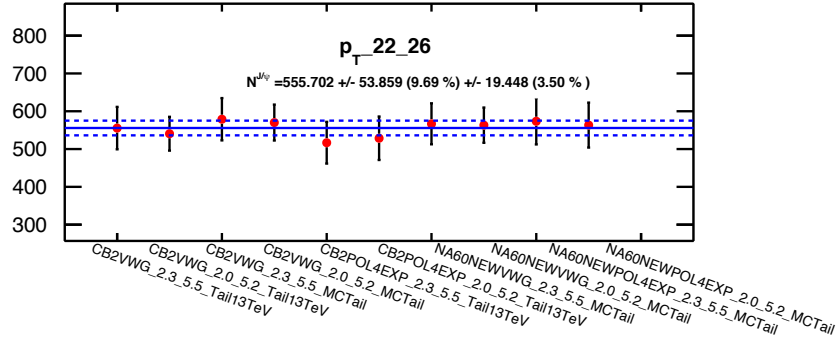


Figure 8.126. J/ψ yield in different set of tests for the p_T bin (22.0, 26.0) GeV/c [116].

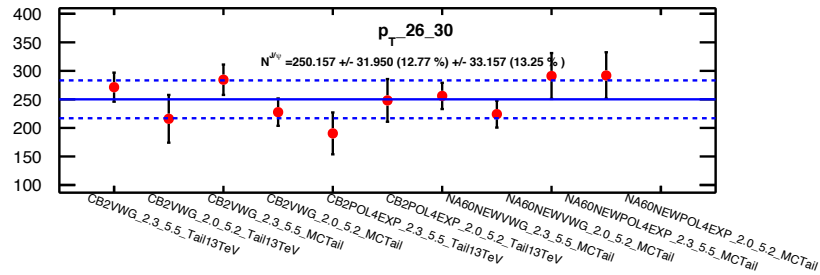


Figure 8.127. J/ψ yield in different set of tests for the p_T bin (26.0, 30.0) GeV/c [116].

8.21 Variation of $\langle p_T^{J/\psi} \rangle$ with invariant mass in the multiplicity bins

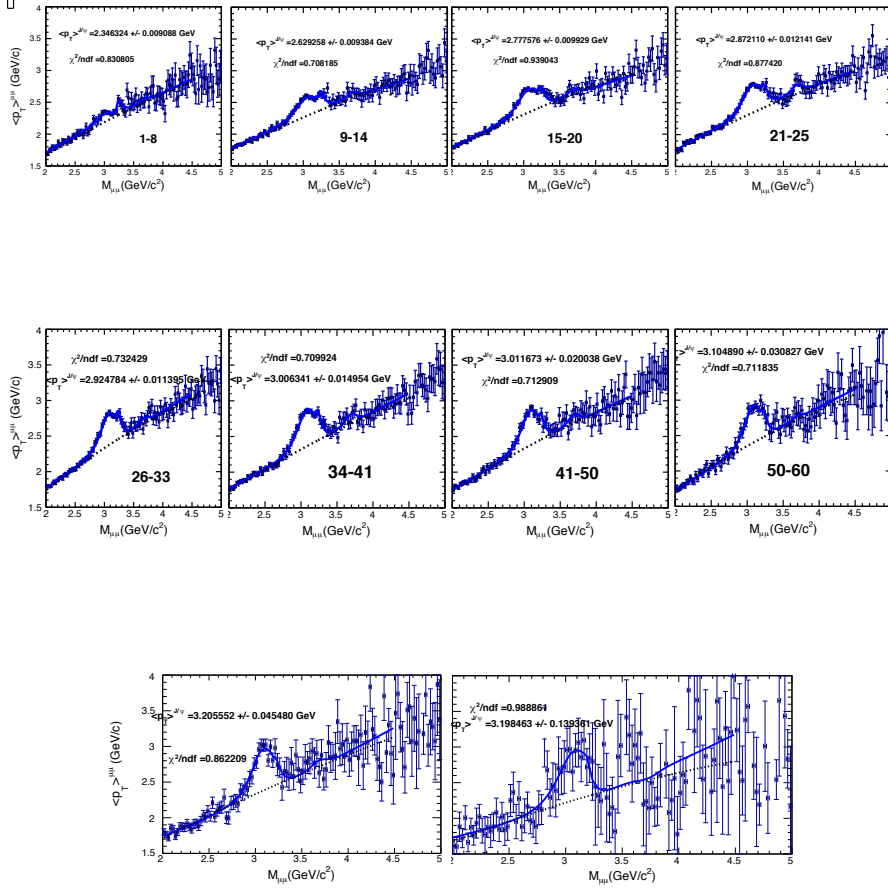
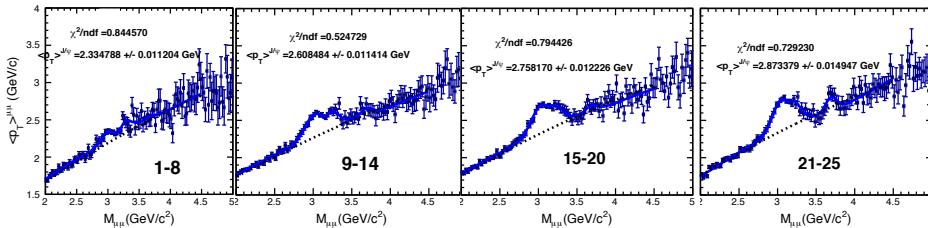


Figure 8.128. Plots of AccEff corrected $\langle p_T^{\mu^-\mu^+} \rangle$ as a function of $m_{\mu^-\mu^+}$. To extract the $\langle p_T^{J/\psi} \rangle$, the invariant mass spectrum is fitted with CB2 + VWG and tail parameters is taken from cross section analysis in pp collisions at $\sqrt{s} = 13$ TeV, where the $\langle p_T^{J/\psi} \rangle$ is parametrized using a “Flat+Linear” function. The second order polynomial (POL2) function is taken as the background function ($\langle p_T \rangle_{\text{bkg}}$) [116].



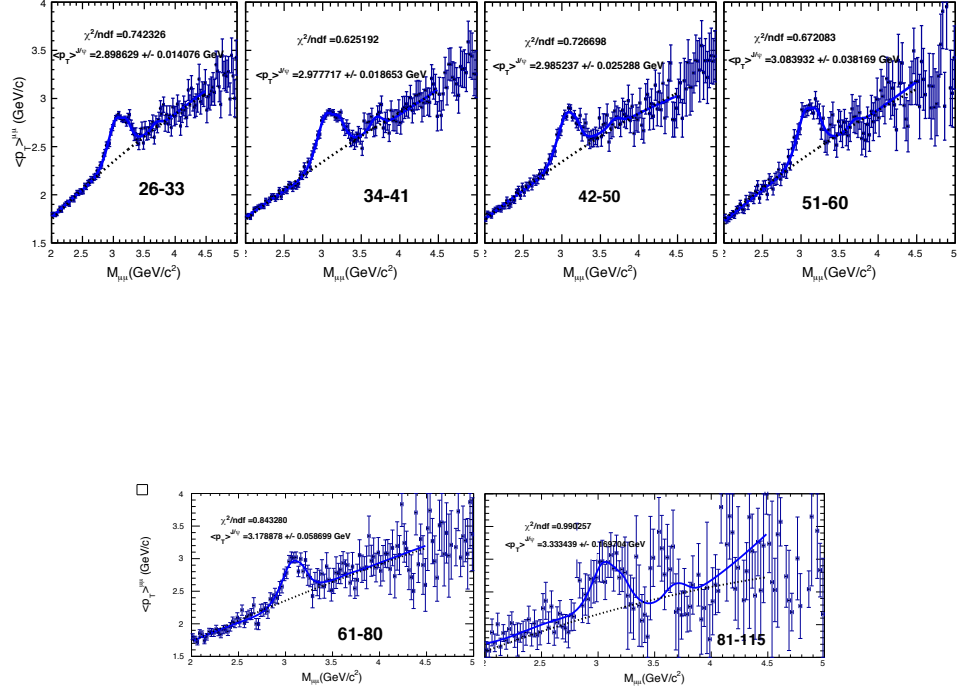


Figure 8.129. Plots of AccXEff corrected $\langle p_T^{\mu^- \mu^+} \rangle$ as a function of $m_{\mu^- \mu^+}$. To extract the $\langle p_T^{J/\psi} \rangle$, the invariant mass spectrum is fitted with CB2 + VWG and tail parameters is taken from cross section analysis in pp collisions at $\sqrt{s} = 13$ TeV, where the $\langle p_T^{J/\psi} \rangle$ is parametrized using a **Pol4(x-3.096)** function. The second order polynomial (POL2) function is taken as the background function ($\langle p_T \rangle_{\text{bkg}}$) [116].

8.22 J/ψ $\langle p_T \rangle$ systematics Plots

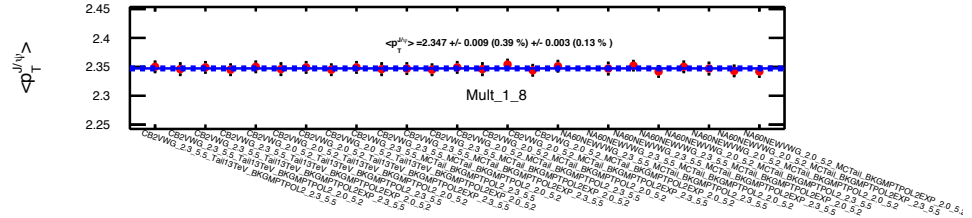


Figure 8.130. J/ψ $\langle p_T \rangle$ in different set of tests for the multiplicity bin (1, 8.0) [116].

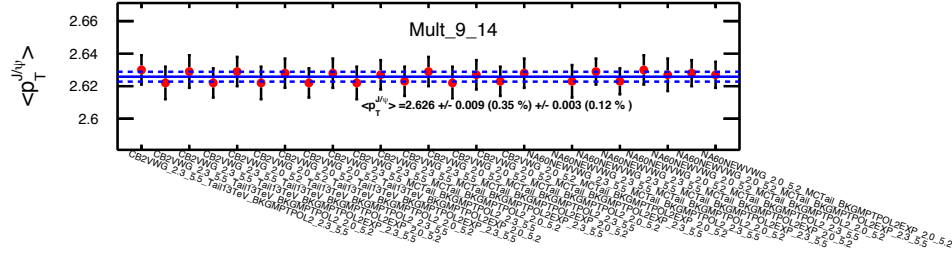


Figure 8.131. $J/\psi < p_T >$ in different set of tests for the multiplicity bin (9.0, 14.0) [116].

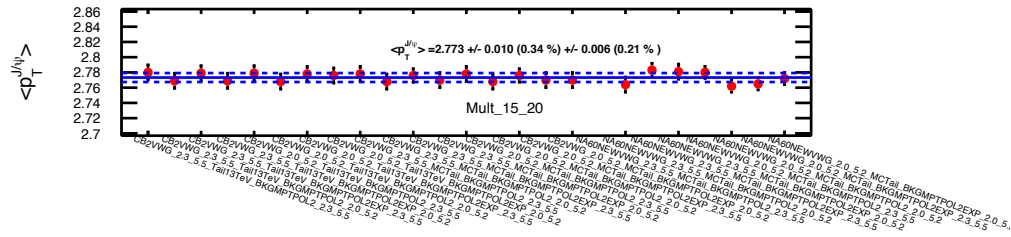


Figure 8.132. $J/\psi < p_T >$ in different set of tests for the multiplicity bin (15.0, 20.0) [116].

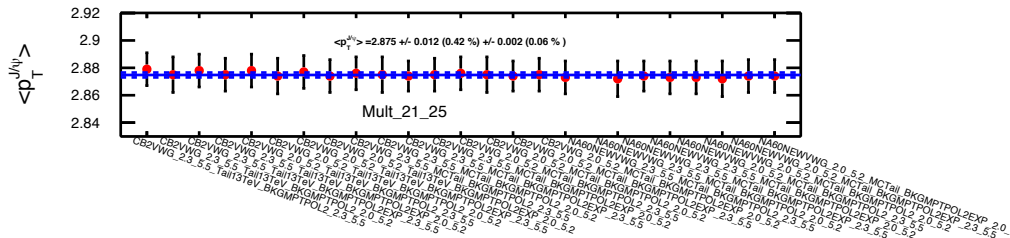
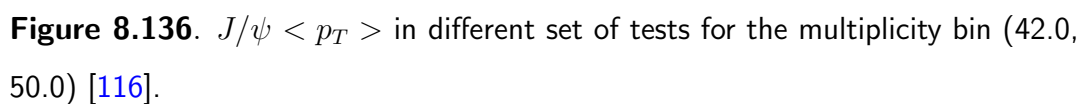
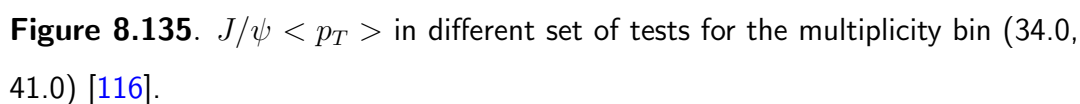
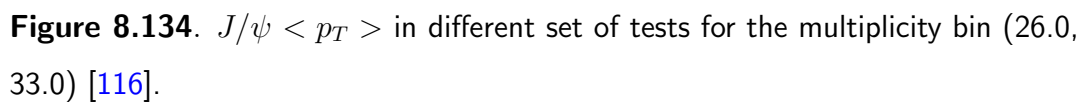


Figure 8.133. $J/\psi < p_T >$ in different set of tests for the multiplicity bin (21.0, 25.0) [116].



8.23 Relative $J/\psi < p_T >$ systematics Plots

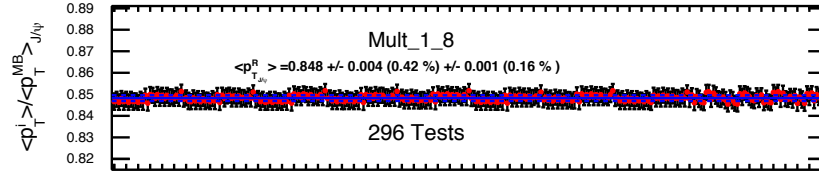


Figure 8.140. Relative $J/\psi < p_T >$ in different set of tests for the multiplicity bin (1, 8.0) [116].

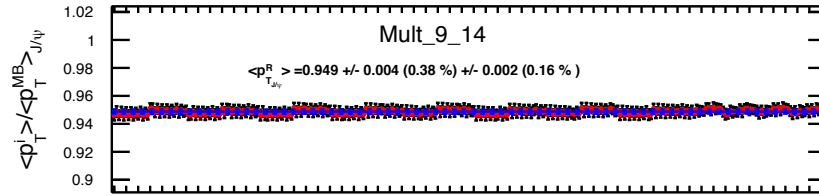


Figure 8.141. Relative $J/\psi < p_T >$ in different set of tests for the multiplicity bin (9.0, 14.0) [116].

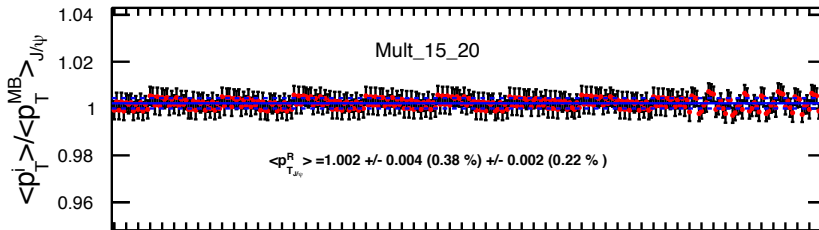


Figure 8.142. Relative $J/\psi < p_T >$ in different set of tests for the multiplicity bin (15.0, 20.0) [116].

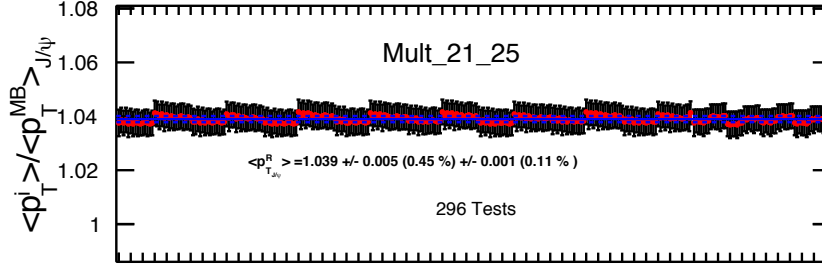


Figure 8.143. Relative $J/\psi < p_T >$ in different set of tests for the multiplicity bin (21.0, 25.0) [116].

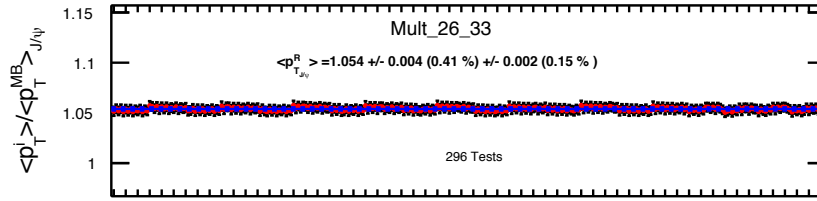


Figure 8.144. Relative $J/\psi < p_T >$ in different set of tests for the multiplicity bin (26.0, 33.0) [116].

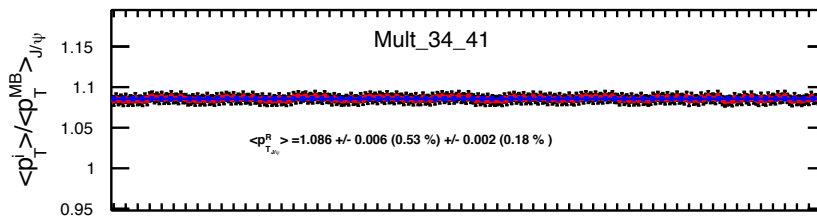


Figure 8.145. Relative $J/\psi < p_T >$ in different set of tests for the multiplicity bin (34.0, 41.0) [116].

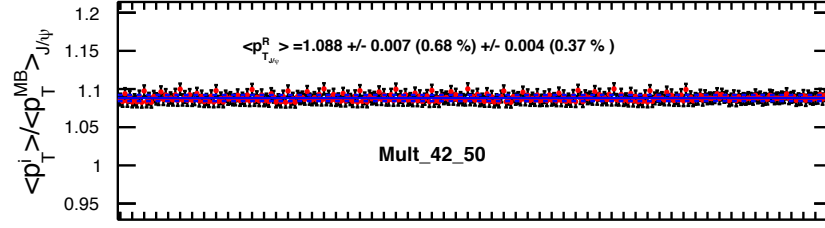


Figure 8.146. Relative $J/\psi < p_T >$ in different set of tests for the multiplicity bin (42.0, 50.0) [116].

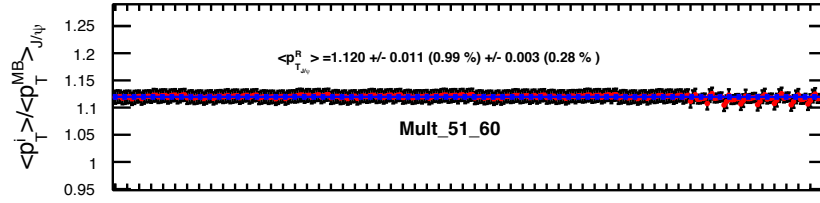


Figure 8.147. Relative $J/\psi < p_T >$ in different set of tests for the multiplicity bin (51.0, 60.0) [116].

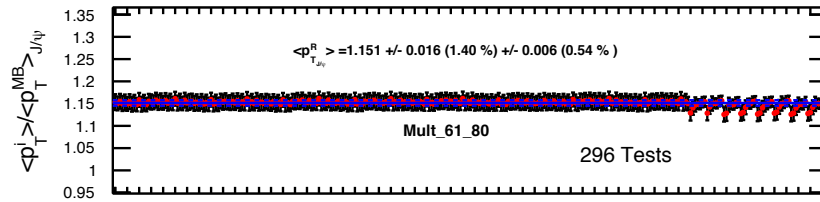


Figure 8.148. Relative $J/\psi < p_T >$ in different set of tests for the multiplicity bin (61.0, 80.0) [116].

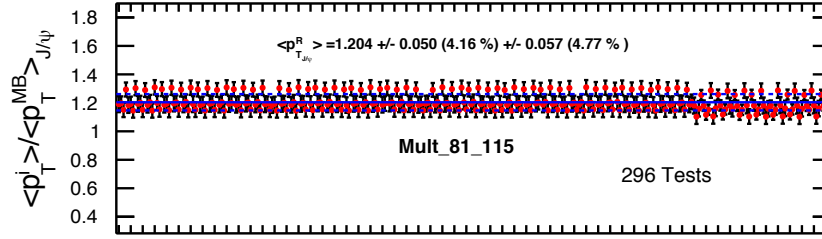


Figure 8.149. Relative J/ψ $\langle p_T \rangle$ in different set of tests for the multiplicity bin (81.0, 115.0) [116].

8.24 Acc X Eff Maps

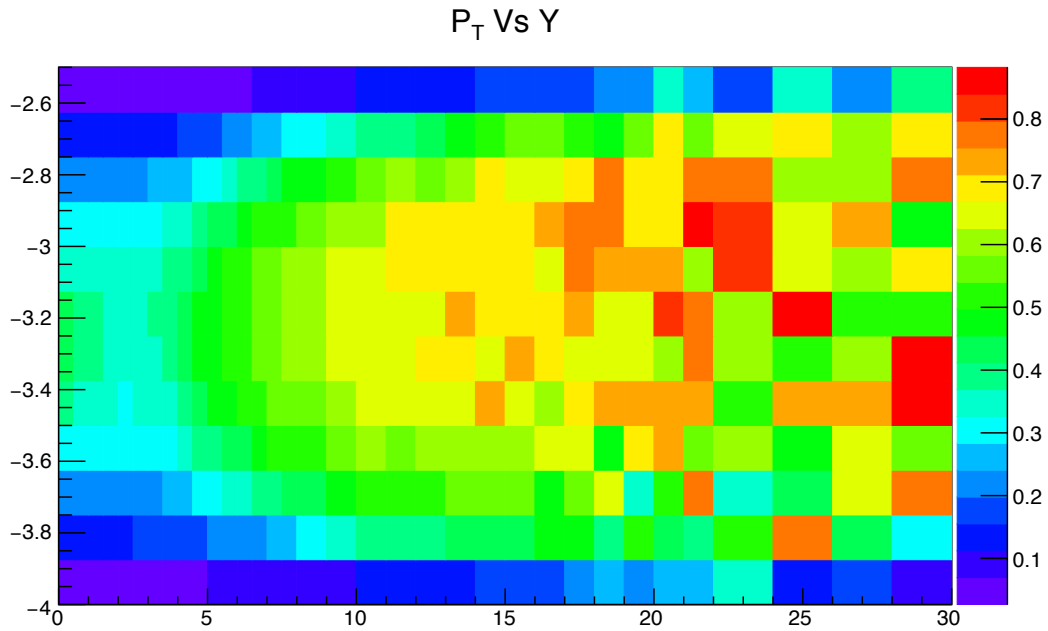


Figure 8.150. Acc X Eff map for the Low-Low combination

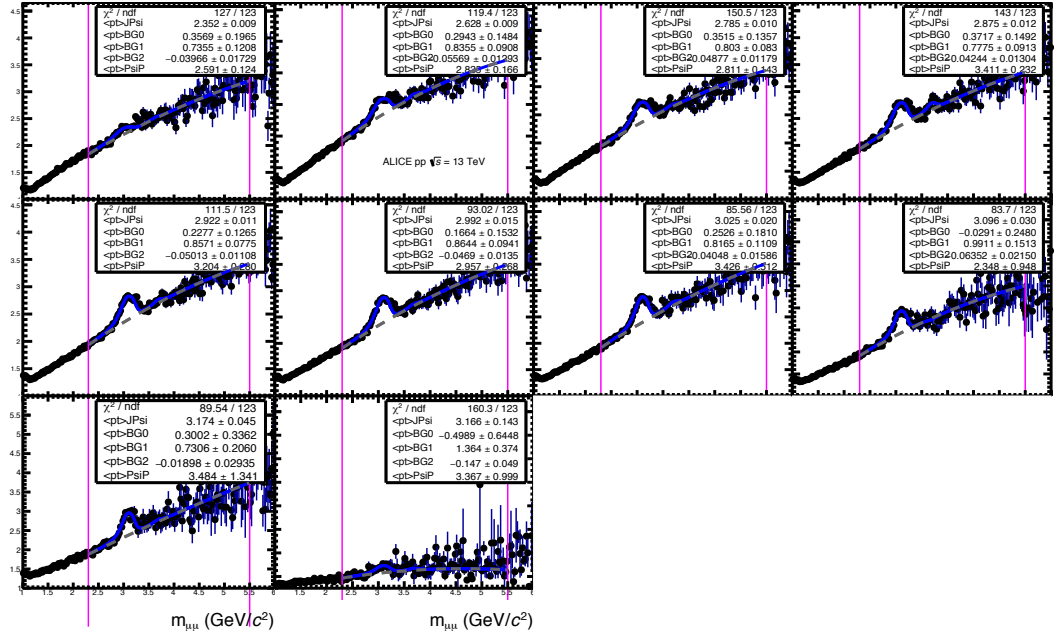


Figure 8.151. Fitting to the dimuon $\langle p_T \rangle$ as a function of invariant mass using Low-Low combination Acc X Eff map, where $CB2 + VWG + Pol2 + 13TeV_Tail$ fitting combination has been used [116].

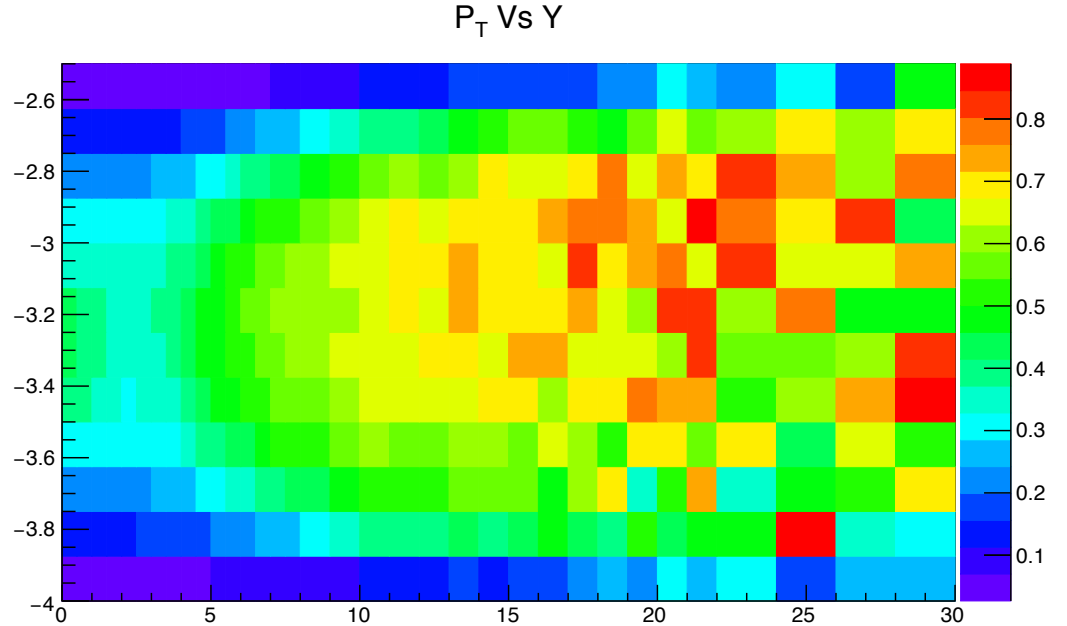


Figure 8.152. Acc X Eff map for the Low-High combination [116].

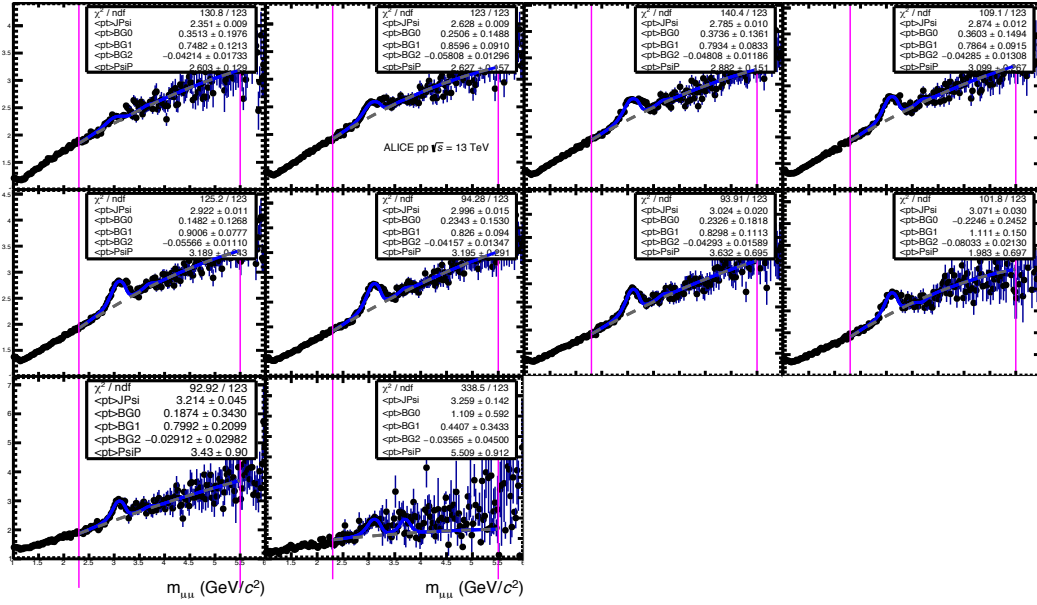


Figure 8.153. Fitting to the dimuon $\langle p_T \rangle$ as a function of invariant mass using Low-High combination Acc X Eff map, where $CB2 + VWG + Pol2 + 13TeV_Tail$ fitting combination has been used [116].

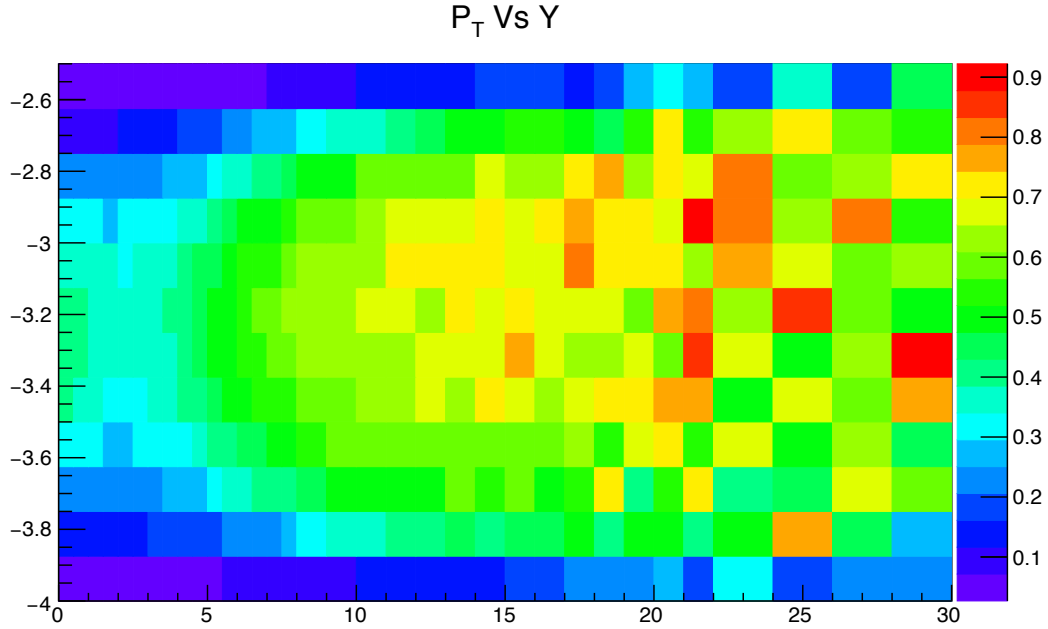


Figure 8.154. Acc X Eff map for the High-Low combination [116].

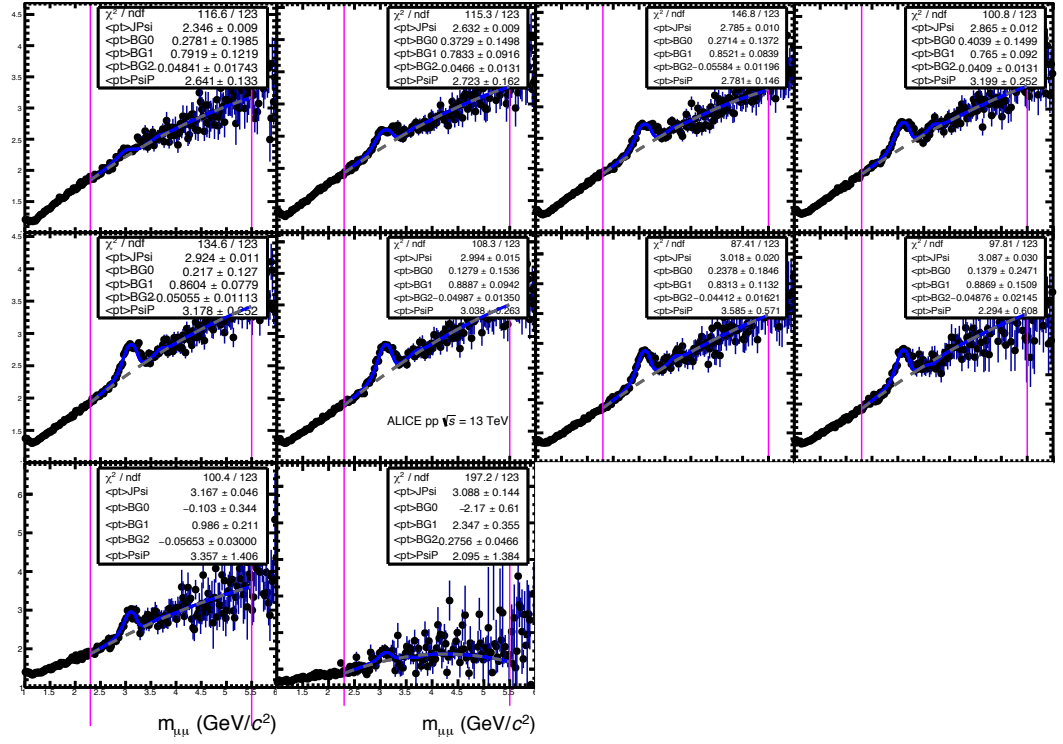


Figure 8.155. Fitting to the dimuon $\langle p_T \rangle$ as a function of invariant mass using High-Low combination Acc X Eff map, where $CB2 + VWG + Pol2 + 13\text{TeV_Tail}$ fitting combination has been used [116].

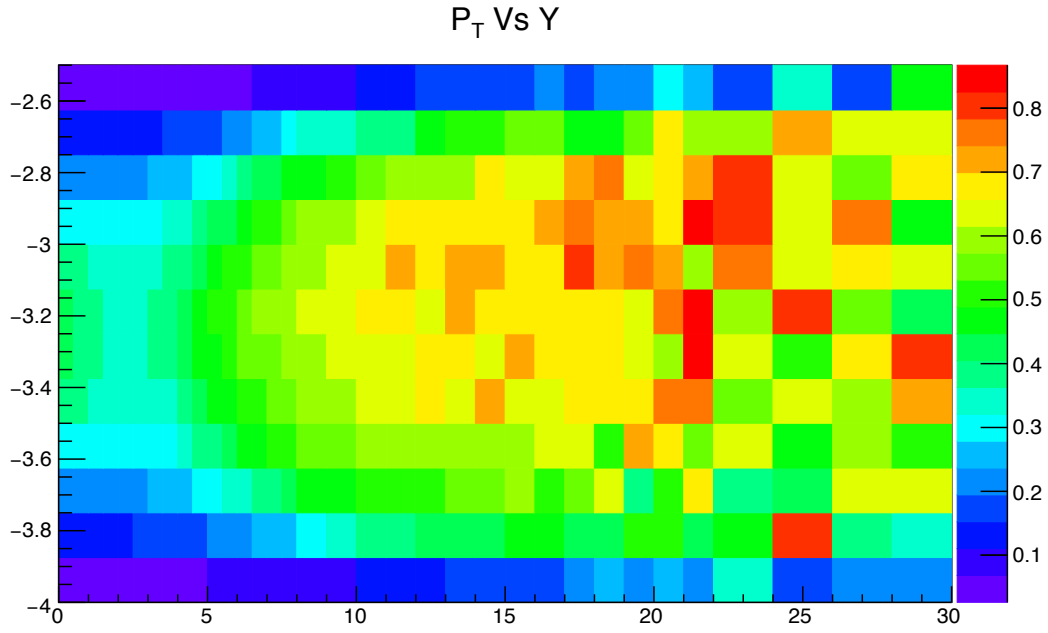


Figure 8.156. Acc X Eff map for the High-High combination [116].

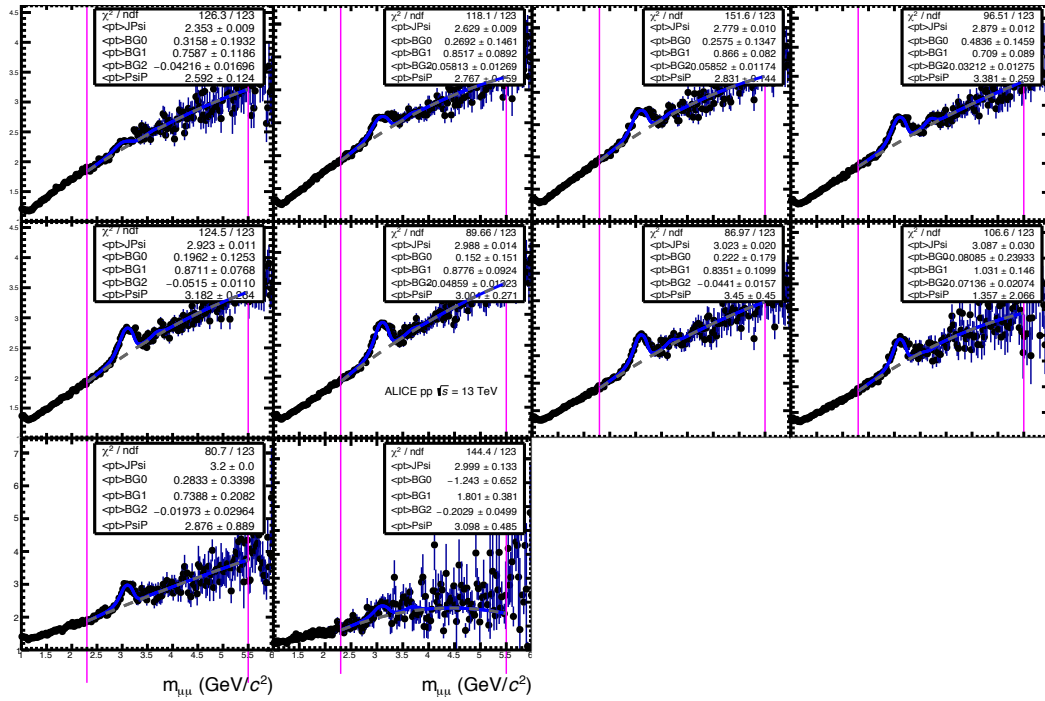


Figure 8.157. Fitting to the dimuon $\langle p_T \rangle$ as a function of invariant mass using High-High combination Acc X Eff map, where $CB2 + VWG + Pol2 + 13\text{TeV_Tail}$ fitting combination has been used [116].

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