

Jet Yields from Dihadron Correlations in PbPb Collisions at 2.76 TeV

BY

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THESIS

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To Stewart

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LIST OF ABBREVIATIONS

ALICE	A L arge I on C ollider E xperiment
ATLAS	A T oroidal L HC A pparatu S
BPTX	B eam P ick-up T iming for E Xperiment
BRAN	B eam R Ate of N eutrals
BSC	B eam S cintillator C ounters
CMS	C ompact M uon S olenoid
DQM	D ata Q uality M onitoring
EB	E lectromagnetic B arrel Calorimeter
ECAL	E lectromagnetic C ALorimeter
EE	E lectromagnetic E ndcaps Calorimeter
HCAL	H adronic C ALorimeter
HEHI	H igh E nergy H eavy I ons
HF	F orward H adronic Calorimeter
HLT	H igh L evel T rigger
HO	H adron O uter Calorimeter
IP	I nteraction P oint

LIST OF ABBREVIATIONS (Continued)

L1	Level 1
LEP	Large Electron-Positron Collider
LHC	Large Hadron Collider
MC	Monte Carlo
PKAM	Previously Known As Monster
PVT	Physics Validation Team
QCD	Quantum ChromoDynamics
QGP	Quark Gluon Plasma
RHIC	Relativistic Heavy Ion Collider
SST	Silicon-Strip Tracker
STAR	Solenoid Tracker At RHIC
TEC	Tracker End Cap
TIB	Tracker Inner Barrel
TID	Tracker Inner Disk
TOB	Tracker Outer Barrel
TOTEM	TOTAL Elastic and Diffractive Cross-Section Measurement
UPC	UltraPeripheral Collisions

LIST OF ABBREVIATIONS (Continued)

ZDC **Z**ero-**D**egree Calorimeter

ZYAM **Z**ero **Y**ield **A**t **M**inimum

SUMMARY

Measurements made using the CMS detector at the LHC of dihadron correlations of charged particles produced in PbPb collisions at nucleon-nucleon center-of-mass energy of 2.76 TeV are presented. The results are studied over a broad range of relative pseudorapidity ($\Delta\eta$) and the full relative azimuthal angle ($\Delta\phi$). The observed two-dimensional correlation structure in $\Delta\eta$ and $\Delta\phi$ is characterized by a narrow peak at $(\Delta\eta, \Delta\phi) \approx (0,0)$ from jet-like correlations, which sits upon a long-range “ridge” structure that persists out to at least $|\Delta\eta| = 4$, and is assumed to be due to hydrodynamic flow. On the “away” side ($|\Delta\phi| \approx \pi$), the jet contribution is spread out quite evenly in $\Delta\eta$ and thus not easily distinguishable from the flow signal. The jet yields of both the near side and the away side are measured. The near-side jet yield is measured by directly subtracting off the ridge contribution. On the away side, where it is not so simple to separate the two, a new method for distinguishing the jet yield from the flow signal is presented along with its results.

CHAPTER 1

INTRODUCTION: A DECADE OF RHIC

1.1 Why Collide Heavy Ions? (For the Layperson)

One microsecond after the big bang, the incredible amount of energy that was initially compressed into the singularity at the center of our universe began to “hadronize”, thus forming the stuff that would one day make up everything and anything we know. Our current understanding is that after this initial microsecond, protons and neutrons were formed, eventually making atoms, then gases, galaxies, stars, and planets. In light of all that has happened in the 15-billion-year history of our universe, one particular microsecond can seem rather insignificant and uninteresting. However, if one begins to ponder the question of what this state of the universe during the unusual period of time after the big bang, but before the formation of matter, actually was like, that particular microsecond can seem quite special.

Not since this first microsecond had this state of matter existed in our universe (that we know), until physicists had the zealous idea to try to recreate these conditions in the laboratory. In the field of high-energy heavy-ion (HEHI) physics, heavy atoms are first stripped of their electrons, then slammed together at near the speed of light. The purpose is to recreate and study this very special moment in history.

To understand how one studies the first microsecond of the universe by colliding lead ions at near the speed of light, one has to first understand some things about matter. Most of the matter in the universe is made up of protons and neutrons, which are specific examples of particles called hadrons. In the critical first microsecond of our universe, the energy density was so high, due to enormous pressures and temperatures, that hadrons simply could not exist, much the way ice cannot exist in a stable way inside your 350-degree oven. However, when hadrons melt, so to speak, something more profound happens than in the case of ice and water. Their mass gets primarily converted to energy, and what exists instead is a quark-gluon plasma (QGP) governed by the strong nuclear force. The familiar phase boundary between solid water (ice) and liquid water has a temperature associated with it (32 degrees Fahrenheit). Similarly, there is a critical phase boundary temperature where hadrons or the “chiral condensate” melts. Theorists, utilizing the techniques of “lattice gauge theory”, have made a prediction of around 2×10^{12} degrees Celsius for the temperature of this phase boundary. To put this in perspective, that is about 100,000,000 times hotter than the surface of the sun. Our estimations of the energy density created in relativistic heavy ion collisions tell us that we were above this temperature by a factor of 5 or so at the Relativistic Heavy Ion Collider (RHIC), an accelerator on Long Island, and we expect to be much higher at the Large Hadron Collider (LHC), the particle accelerator used to collect the data in this thesis.

We believe we are melting protons and neutrons into a quark-gluon plasma similar to the one that existed right after the big bang¹.

The quark-gluon plasma cannot be directly observed. This is due in part to the fact that quarks and gluons are fundamentally very different from the particles we are used to. They can never exist in quantum-mechanically “observable” states like hadrons such as protons and neutrons can. In order to form observable particles, they must bind with each other in very specific ways governed by the laws of “quantum chromodynamics”. In the quark-gluon plasma, hadronic matter has melted and conditions are too hot for quarks to bind with each other. In order to study the plasma, we must wait for it to cool and freeze into new particles that radiate out into our detector². It is from these particles that we try to reconstruct the properties of the plasma itself.

To study the plasma, we exploit the fact that proton collisions of the same beam energy are not expected to create the quark-gluon plasma found in heavy-ion collisions. Many of the measurements in heavy-ion physics are actually comparisons of features between proton collisions and heavy-ion collisions. This thesis is concerned with the yields and shapes of “dijets”.

¹Technically, the quark-gluon plasma created in the laboratory is thought to be “strongly” interacting, where the one created in the big bang was thought to be more “weakly” interacting.

²The wait is actually only around a billionth of a billionth of a second.

When a hard scattering occurs in a proton collision, two scattered partons (quarks or gluons) will fly apart in opposite directions constantly pulling other quarks out of the vacuum that recombine to form showers of observable particles known as jets. Collisions that produce jets in opposite directions are known as “dijet events”, Figure 1 (left).

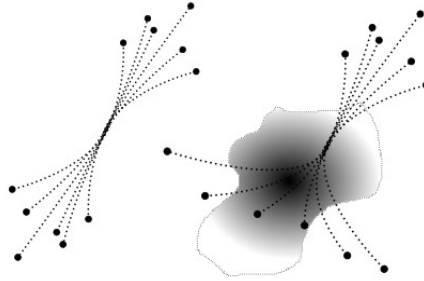


Figure 1. An illustration of a dijet event from a proton collision (left) and a dijet immersed in a quark-gluon plasma (right)

Dijets make an excellent probe of the plasma in the following sense. When we look at dijet events where one jet has passed through the plasma, and the other jet has not, we can learn a great deal about the properties of the plasma from the modified shape of the jet that has traversed the plasma. To understand what we are looking at, these dijets produced in heavy ion collisions must be compared to dijets produced in proton collisions where there is no plasma. For example, one expectation is that a jet that travels through

the plasma comes out the other side more spread out and with lower energy compared to a jet that doesn't traverse the plasma (Figure 1).

Among the things that could be learned is the nature of the energy loss mechanism in the plasma. Simply understanding how much energy is lost to the plasma as a function of how fast the quark is traveling through it would be extremely useful to theorists to better understand the fundamentals of matter. Another measurement that could potentially be made is the sound speed of the plasma, which could be deduced by measuring the angle of a mach-cone shock wave left by the quark (if such a shock wave exists). This phenomenon would be similar to how a passing speed boat leaves a triangle shaped wake on water. By knowing the speed of the boat and the angle of the wake one can deduce the speed of the water waves, which tells us about the density and surface tension of water. Gaining understanding of what happens when a jet passes through the medium was the original motivation behind many correlation studies at the Relativistic Heavy Ion Collider (RHIC) in the latter half of the last decade. This thesis continues the work done at RHIC, but at higher energy density and in finer detail.

1.2 A Bit More Technical

The current understanding is that the universe underwent a series of phase transitions shortly after the big bang. At 10^{-11} seconds and a temperature around 100 GeV/ k_B , the electroweak phase transition occurred, giving Higgs mass to most of the elementary particles (1). At 10^{-5} seconds and a temperature of around 200 MeV/ k_B , a phase transition

governed by the strong force took place and the quarks and gluons combined into bound hadronic states and chiral symmetry was broken (2). The state of matter just before this strong-force phase transition is the quark-gluon plasma which is the subject of heavy-ion physics.

Quantum Chromodynamics (QCD) is the theory that governs the strong force. Because quarks and gluons are QCD's fundamental degrees of freedom, the quark-gluon plasma can provide much input and insight into QCD. A key feature of QCD is that the gluon (the gauge boson of the theory) can couple to itself. This leads to the coupling constant having an inverse dependence on the momentum transfer in an interaction. This unique property of QCD gives rise to asymptotic freedom, where the interaction between quarks becomes arbitrarily weak at arbitrarily small length scales. Another consequence of the scalable QCD coupling constant is color confinement, where constituent quarks cannot be observed as free particles.

It is expected that this strong force phase transition takes place around energy density $\epsilon = 1 \text{ GeV/fm}^3$ and temperature around 200 MeV/k_B (3). This puts the transition in a regime where the strong coupling constant is too large to be calculated with perturbative QCD. Information on the equation of state can be provided by Lattice QCD, where the field equations are solved numerically on a discrete space-time grid. For an ideal massless gas, which is expected at extreme temperatures, the equation of state is given by:

$$\begin{aligned}
P &= \frac{1}{3}\epsilon \\
\epsilon &= g \frac{\pi^2}{30} T^4
\end{aligned}
\tag{1.1}$$

where P is the pressure, ϵ the energy density, T the temperature and g the effective number of degrees of freedom. Every bosonic degree of freedom contributes 1 to g , while fermionic degrees of freedom count as $\frac{7}{8}$. A three-flavor QGP has $g = 47.5$, whereas a pion gas has $g \approx 3$. In Figure 2 one can see a dramatic increase in energy density as calculated from Lattice QCD around $T = 200$. This is due to a dramatic increase in the number of degrees of freedom, g , as quarks and gluons are freed from confinement (4).

Relativistic heavy-ion collisions are an excellent tool for studying hot QCD matter and its phase transition. Like shortly after the big bang, the hot, dense system is expected to cool and expand rapidly, during which time the system experiences a wide range of energy densities and temperatures, and likely different phases of matter. It is thought that the system will rapidly thermalize after the collision and form the QGP which then expands and ultimately re-hadronizes.

High-energy particle physics and high-energy heavy-ion physics have in common a rich history with much overlap. The Tevatron at Fermilab National Laboratory first accelerated protons to an energy of 512 GeV/c in 1983, and in 1985 began colliding protons and antiprotons at a center-of-mass energy of 1.6 TeV/c. Heavy-ion physics is

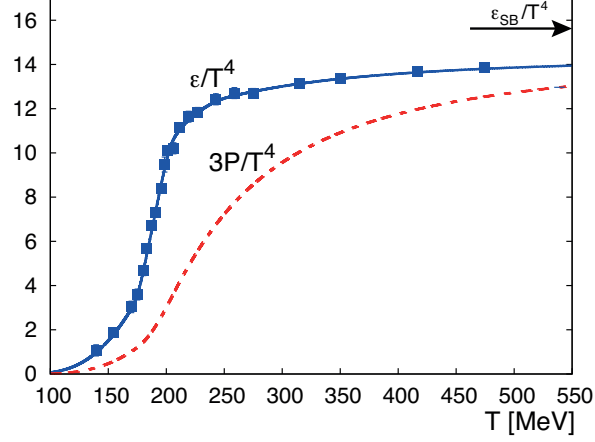


Figure 2. Energy density ϵ/T^4 (blue solid line) and pressure $3P/T^4$ (red dashed line) as a function of temperature T from lattice calculations. The arrow indicates the Stefan Boltzmann limit of the energy density (4).

however much more recent, with the Relativistic Heavy Ion Collider (the first of its kind) first coming on-line in 2000 (5), reaching energies of 200 GeV/c per nucleon pair.

One might have naively thought that since a heavy ion is composed of multiple nucleons, a heavy-ion collision would behave no differently than the superposition of multiple nucleon-nucleon collisions. This is in fact not the case. The underlying physics of a high-energy heavy-ion collision is quite different due to the energy density of the system being above the QCD phase boundary between the hadron gas and the QGP (6; 7). The nuclear matter phase diagram (as it was understood by the Department of Energy and the National Science Foundation in 1983) which inspired physicists to build RHIC is shown in Figure 3. It is not hard to imagine the excitement of physicists in the early eighties sit-

ting together making this drawing and pointing to the the dotted lines, which represent the trajectories in phase space which could be explored by ultra-relativistic heavy-ion collisions. It would be another 17 years before they would have the satisfaction of seeing RHIC achieve such collisions.

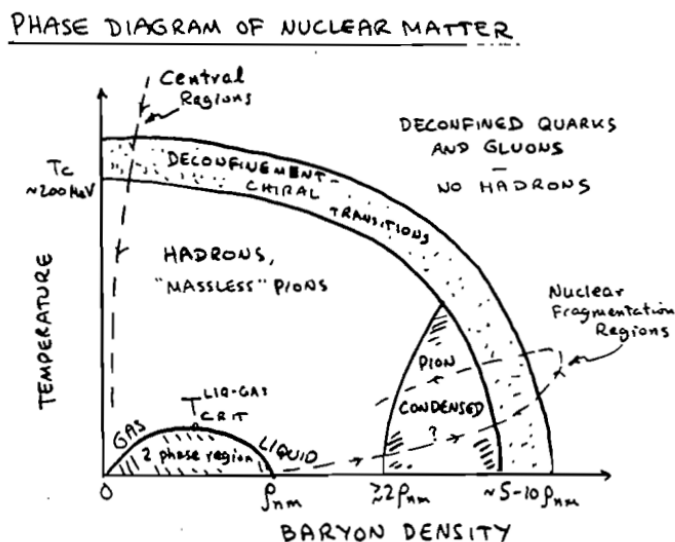


Figure 3. Expected phases of nuclear matter at various temperatures and baryon (or nucleon) densities, showing the “hadronic phase” including a gas-liquid phase transition region, and the transition region to deconfined quarks and gluons.

From the 1983 NSAC Long Range Plan (8).

1.3 The Glauber Model and the Centrality Variable

In principle, two ions can collide head on, just glance by each other, or collide with any “centrality” in between. Varying the impact parameter, b (see Figure 4) in a heavy-ion collision can provide very useful information. In the extreme case of $b = 0$ (head on collision), one expects the most energy transfer, and the hottest, densest QGP. In the case of a peripheral collision (large b), where only a few nucleons interact on the periphery, the result can be very similar to a proton-proton collision with no QGP formation.

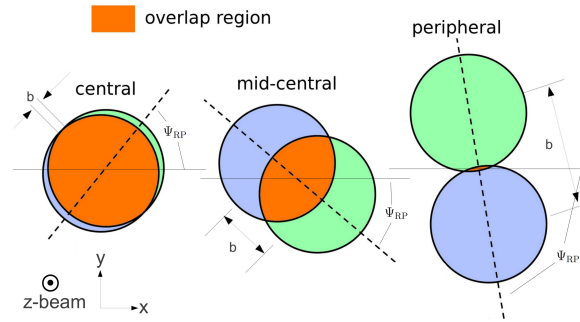


Figure 4. A drawing of a central, mid-central, and peripheral heavy-ion collision from the vantage point of looking down the beam axis (z-axis). The “reaction plane”, defined as the plane made by the z-axis and the line between the centers of the colliding nuclei, is shown as a dotted line. The “reaction plane angle”, Ψ_{RP} , defined as the angle between the reaction plane and the x-axis, as well as the impact parameter, b , are also shown for all three example collisions.

If one could vary the impact parameter one could in effect gradually turn on and off the QGP, and study its exact behavior with respect to system size, shape, and density. In reality, not only can the impact parameter not be controlled, but it cannot be measured. It is expected to correlate, however, with a few observables that can be measured. Because the more central the collision, the greater the energy transfer, one expects central collisions to have the greatest final state multiplicity and energy from particles with trajectories transverse to the beam axis. Also, the number of neutrons that break off of the nucleus and continue in a straight line after the collision (they do not bend in the magnetic field) will correlate with centrality. Thus the energy deposited in zero-degree calorimeters (ZDCs) located far from the collision point along a straight line trajectory will also correlate with centrality.

Typically events are divided into centrality classes, or percentiles. For example, the 10 percent of collisions which have the highest energy deposited in a particular detector will be called the 10 percent most central events. In a mid-peripheral collision, there will be some overlap region between the two colliding nuclei. Nucleons that fall within the overlap region are called “participants” while nucleons that are outside the overlap region are called “spectators”. Figure 5 illustrates the participants and the spectators.

The Glauber Model of a heavy-ion collision considers the collision to be a superposition of many constituent nucleon-nucleon collisions. It is a model that allows for the understanding of the centrality variable in terms of the number of participants or in terms

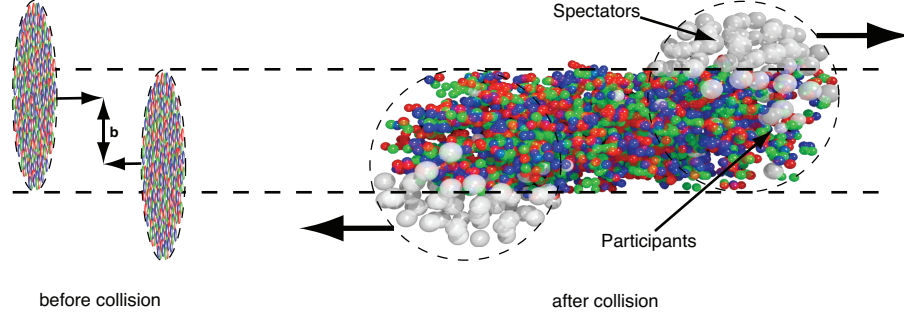


Figure 5. A drawing of a heavy-ion collision before impact (left) and after impact (right). The nuclei are flattened in the direction of travel due to Lorentz contraction. The participants are the nucleons that interact in the collision, while the spectators are the nucleons that continue down the beam pipe as part of a broken nucleus.

of the number of binary collisions. Glauber calculations have provided an astonishing amount of information considering how simple the model actually is. The basic assumption is that the nucleus travels in a straight line, which at high energies is a very good approximation. The nucleus is modeled as having a spherically symmetric distribution of nucleons with radial density given by the Woods-Saxon distribution. Individual nucleons are tracked in straight-line trajectories and the number of participants “ N_{part} ” as well as the number of binary collisions “ N_{coll} ” with other nucleons is counted. Example results of a Glauber Monte Carlo simulation are shown in Figure 6. N_{coll} scales as roughly $\left(\frac{N_{\text{part}}}{2}\right)^{4/3}$, as each participant can have multiple binary collisions as it passes through the other nucleus.

Typically, the data are divided into centrality percentiles as small as good statistics will

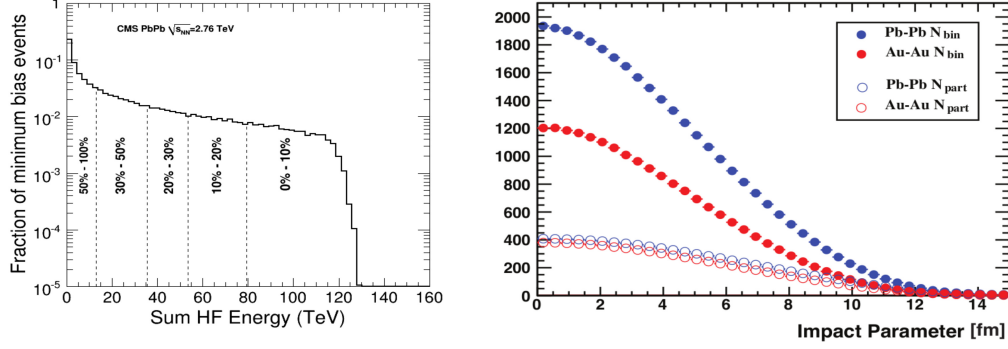


Figure 6. Energy deposition distribution for PbPb collisions at $\sqrt{s_{NN}} = 2.76$ TeV/c measured by the CMS detector, showing an example classification in centrality percentiles (left). Number of participating nucleons N_{part} and binary collisions N_{coll} (sometimes notated as N_{bin} or N_{binary}) vs impact parameter for PbPb at $\sqrt{s_{NN}} = 2.76$ TeV/c and AuAu at $\sqrt{s_{NN}} = 200$ GeV/c (right).

allow, and the average N_{part} and N_{coll} values are calculated for each percentile by dividing the results of a Glauber Monte Carlo simulation as in Figure 6 into the same percentiles. Heavy-ion results are then often plotted as a function of average N_{part} .

1.4 R_{AA}

In nucleon-nucleon collisions, fragmentation from hard scattered partons (quarks or gluons) produces showers of particles called jets. It is expected that hard scatterings in heavy-ion collisions occur before the formation of the QGP, and that a parton traveling through the created medium will lose energy through gluon bremsstrahlung (9). The

main observable consequence of this “jet-quenching” is suppression in the yield of high-transverse-momentum (high- p_T) hadrons (10).

This suppression is typically quantified by the ratio, R_{AA} , as given by:

$$R_{AA}(p_T) = \frac{(1/N_{Evt})d^2N^{A+A}/dp_Td\eta}{(\langle N_{coll} \rangle / \sigma^{N+N})d^2N^{N+N}/dp_Td\eta} \quad (1.2)$$

The numerator in Equation 1.2 is the per-event-scaled differential hadron yield for heavy-ion collisions as a function of p_T and pseudorapidity, η , where $\eta = -\ln(\tan(\theta/2))$ and θ is the polar angle of the particle with respect to the beam axis. The denominator is the same quantity for pp collisions written in terms of the cross-section, but also includes the average number of binary collisions from the A+A result, N_{coll} , as a scaling factor to make the denominator comparable to the numerator.

R_{AA} is calculated as follows: A baseline expectation is found by scaling pp results by N_{coll} , as predicted by the Glauber model (11). The ratio is taken between what is actually observed to this baseline. In other words, R_{AA} is the ratio of what one actually gets in a heavy-ion collision, to what one would get if a heavy-ion collision were nothing more than the superposition of many nucleon-nucleon collisions.

The PHENIX Collaboration (one of the detectors at RHIC) found in 2002 that in gold-gold (AuAu) collisions at $\sqrt{s_{NN}} = 200$ GeV, at mid-rapidity ($\eta \approx 0$) for both charged and neutral particles with $p_T > 2$ GeV/c, R_{AA} was consistent with unity for peripheral collisions (12). This was to be expected as peripheral collisions are in fact the collision of

a few nucleons on the periphery of a nucleus as it passes by another, and should therefore be similar, if not identical to a few superposed pp collisions. A much more interesting result of this study was the fact that for central collisions, where the QGP is expected, R_{AA} was found to be significantly less than 1 for charged particles with $p_T > 2$ GeV/c. The suppression by a factor of 5, which was found to hold at least up to the upper p_T limit of the analysis of 4 GeV/c, was especially striking because R_{AA} for p-Au collisions, had been known to be greater than 1 (≈ 1.3) at 4 GeV/c due to the Cronin effect (13). The difference between pp collisions and heavy ion collisions was for the first time found to be a very dramatic effect. RHIC has also collided deuteron with gold (dAu) at $\sqrt{s_{NN}} = 200$ GeV/c as a crosscheck for many measurements including R_{AA} . The quantity R_{dA} (like R_{AA} , but the ratio is taken for dAu to pp), was also measured by the PHENIX Collaboration and is shown in Figure 7 (left) along with R_{AA} . For charged hadrons and neutral pions, one sees an enhancement due to the Cronin effect for dAu, but very clear strong suppression for charged hadrons in central AuAu.

In Figure 7 (right) one sees that R_{AA} for neutral pions converges with unity for peripheral collisions, but is strongly suppressed in central collisions. The fact that R_{AA} for direct photons is consistent with 1 is an important cross check. Since photons are not influenced by the strong force, they are expected to traverse the QGP un-modified. A value of 1 for photon- R_{AA} means in particular that N_{coll} is the correct scaling factor, and is being calculated correctly by Glauber Monte Carlo simulations.

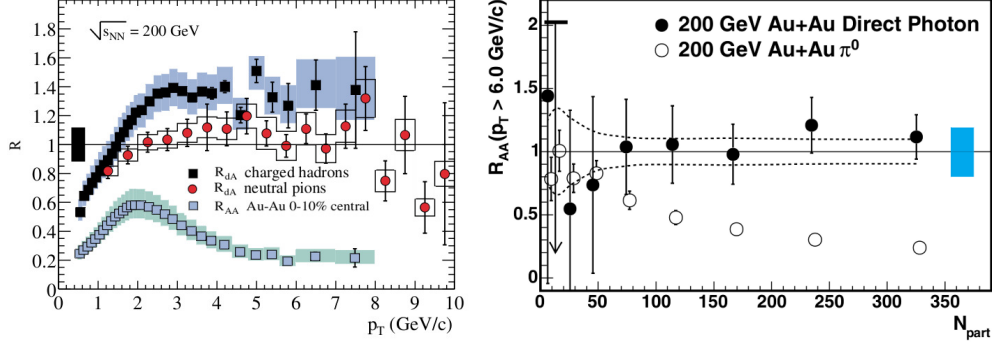


Figure 7. R_{AA} and R_{dA} as a function of p_T for $(h^+ + h^-)/2$ and π^0 mesons in minimum bias dAu collisions and $(h^+ + h^-)/2$ for the 10% most central AuAu collisions at $\sqrt{s_{NN}} = 200$ GeV/c as measured by the PHENIX Collaboration (14) (left). R_{AA} as a function of N_{part} for direct photons and π^0 mesons integrated above 6 GeV/c for AuAu collisions at $\sqrt{s_{NN}} = 200$ GeV/c as measured by the PHENIX Collaboration (15) (right).

The discovery of hadron suppression represented by R_{AA} measurements in RHIC represented the first evidence of the formation of the strongly-interacting quark gluon plasma predicted by quantum chromodynamics.

1.5 Elliptic Flow

When the mean free path of the particles in a system becomes smaller than the system size itself, a description of the system in terms of macroscopic observables and bulk behavior is appropriate. The QGP is expected to be such a system, thus multiple interactions between the constituents of the medium should produce macroscopic collective behavior or flow. In a system that flows as it expands, initial state spatial anisotropies result in final state momentum anisotropies, as a result of pressure gradients. In central collisions, the overlap region between the two nuclei as seen from the beam axis is approx-

imately round, however as collisions become less central, the region becomes more of an almond shape. This results in an initial state azimuthal anisotropy in the plasma created in mid-central collisions. The final-state azimuthal anisotropy is routinely decomposed into a Fourier series in 3-vector differential distributions given by:

$$E \frac{d^3N}{d^3\mathbf{P}} = \frac{1}{2\pi} \frac{d^2N}{p_T dp_T dy} \left(1 + 2 \sum_{n=1}^{\infty} v_n \cos[n(\phi - \Psi_{RP})] \right) \quad (1.3)$$

where E is the energy of the particle, $\mathbf{P}$, the 3-vector momentum, p_T , the transverse momentum, ϕ , the azimuthal angle, y , the beam rapidity, and Ψ_{RP} the reaction plane angle illustrated in Figure 4. Because of the almond shaped overlap region, the most significant contribution to Equation 1.3 for all but the most central collisions is the v_2 term, which is usually called elliptic flow.¹ There is an inconsistency in the common lexicon regarding what the “true” meaning of v_2 is that is worth mentioning. Although the definition is precise in terms of the Fourier expansion in Equation 1.3, most physicists use the term v_2 to mean the contribution to the Fourier expansion that comes from hydrodynamic flow. Thus the meaning of “true” v_2 in the common lexicon excludes contributions from jets to the mathematical second Fourier coefficient with respect to the reaction plane. There are several methods of measuring v_2 , each with different sensitivity

¹Strictly speaking, there is nothing “elliptical” about elliptic flow. Neither the shape of the overlap region nor the shape described by $1 + 2v_2\cos(2\phi)$ are mathematical ellipses, but rather more “almond” and “peanut” shapes respectively.

to “non-flow” effects, including the Reaction Plane Method (16), 2-particle and 4-particle Cumulant Methods (17), and most recently, a Fourier Decomposition Method (18).

1.6 Correlations and Away Side Suppression

After observing the suppression of high p_T hadrons in central AuAu collisions at $\sqrt{s_{NN}} = 200$ GeV/c discussed in Section 1.4, one might think to ask which hadrons are missing. Is the suppression uniform in ϕ and η , or is there some spatial dependence? Since the energy loss is primarily predicted to be due to gluon bremsstrahlung of a high- p_T parton traversing the medium (9), it makes sense to look in the direction of the high- p_T parton, in particular for the suppression. It is of course not possible to look at an event display of a single collision and see which hadrons are missing. A statistical analysis needs to be performed.

The technique of correlating “dihadron” pairs has been an effective technique in measuring hadron suppression since the STAR Collaboration (Solenoid Tracker At RHIC) first published evidence of “away side” suppression in 2003 (19). STAR correlated high- p_T “trigger” particles ($4 < p_T^{\text{trig}} < 6$ GeV/c) with lower- p_T “associated” particles ($p_T^{\text{assoc}} > 2$ GeV/c) in azimuthal angle ϕ , for different centrality classes in $\sqrt{s_{NN}} = 200$ GeV/c AuAu collisions.

In this study, for each trigger particle in the event, the number $N(\Delta\phi, \Delta\eta)$ of “associated” particles was incremented as a function of their relative azimuth ($\Delta\phi$) and

pseudorapidity ($\Delta\eta$) with respect to the trigger particle. The overall azimuthal pair distribution per trigger particle was then constructed as

$$D(\Delta\phi) = \frac{1}{N_{\text{trigger}}} \frac{1}{\epsilon} \int d\Delta\eta N(\Delta\phi, \Delta\eta) \quad (1.4)$$

where N_{trigger} is the number of particles satisfying the trigger requirement, ϵ is an efficiency parameter, and the range of integration was taken to be $|\Delta\eta| < 1.4$ in this case. This expression is equivalent to $\frac{1}{N_{\text{trigger}}} \frac{dN}{d(\Delta\phi)}$.

This technique was also performed for pp collisions at the same energy, and for each centrality in AuAu, the result was compared to the pp result plus the expected elliptic flow contribution. For peripheral events, the two measurements agreed in all $\Delta\phi$, however in the 5% most central events, suppression of the AuAu result was seen on the “away side” ($\Delta\phi \approx \pi$), while the “near side” ($\Delta\phi \approx 0$) agreed with pp. This classic result is shown in Figure 8 (left).

Figure 8 (right), taken from STAR’s 2003 follow-up study (21), shows that away-side suppression is not seen in cold nuclear matter, as in dAu collisions. This plot elegantly and profoundly demonstrates to physicists that there is something unusual going on in central heavy-ion collisions. Central AuAu, dAu, and pp all line up on the near side, but central AuAu was found to be perfectly flat on the away side. In this particular centrality and range of p_T^{trig} and p_T^{assoc} the away side jet structure is simply missing, consistent with a dramatic softening of jet fragmentation in dense matter, arising from strong partonic

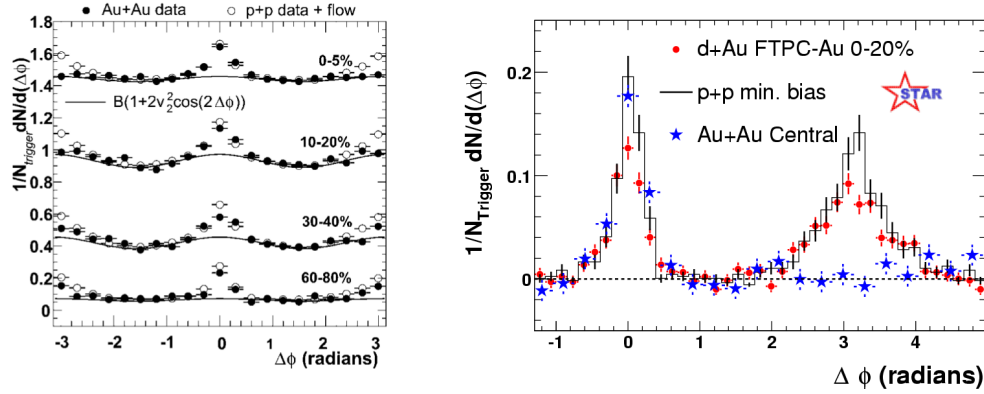


Figure 8. Associated yield for dihadron pairs in $\sqrt{s_{NN}} = 200$ GeV/c AuAu collisions for 4 centrality classes superimposed over pp results plus an elliptic-flow factor. For the 5% most central data, there is strong suppression on the away side. From (19) (left). Associated yield for dihadron pairs for dAu, pp, and most 20% AuAu at $\sqrt{s_{NN}} = 200$ GeV/c. The suppression on the away side is much more clear and striking. From (20) (right).

energy loss as predicted (9). Due to the increasingly clear indication of the creation of the QGP, this plot and Figure 7 (left) made up two of the four plots on the cover of Physics Review Letters in 2003. This was an exciting time for heavy-ion physics.

1.7 The Ridge and the Double Hump

In the years between 2005 and 2010, as more data was collected at RHIC, statistics allowed for more and more detailed correlations studies. It became increasingly common to show both the $\Delta\phi$ and the $\Delta\eta$ correlation in two dimensions. The $\Delta\eta$ dimension brings several features to light that are not visible in a 1-dimensional $\Delta\phi$ correlation plot. In a binary-collision-like correlation plot, such as for pp, dAu, or peripheral AuAu,

on the near side, one expects a peak around (0,0) to be roughly Gaussian with the same width in both dimensions. However, on the away side ($\Delta\phi \approx \pi$), because the interacting partons can carry any fraction of the nucleon momentum, one expects the away side jet to be spread out in $\Delta\eta$. These effects can be seen in Figure 9 (left) (22).

Given that dihadron-correlation techniques correlate particles with other particles from the same event in azimuthal angle ϕ , final state anisotropies will have an impact on the correlation. The elliptic flow effect found in mid-central heavy-ion collisions will contribute an overall $\cos(2\Delta\phi)$ term with magnitude $\langle v_2^{trig} \rangle \times \langle v_2^{assoc} \rangle$, where $\langle v_2^{trig} \rangle$ is the average v_2 for the p_T range of the trigger particles, and $\langle v_2^{assoc} \rangle$ is the average v_2 for the p_T range of the associate particles. The effect of an overall $\cos(2\Delta\phi)$ contribution to the correlation function will not be so visible on the away side, where there is already a mound extending uniformly in $\Delta\eta$ due to the away-side jet contribution. However on the near side, its effect would be seen as an extra ridge that the near-side jet would appear to sit upon. Typically, at least until recently, v_2 was measured, and the effect was subtracted from the correlation.

One of two big surprises that turned up using this technique was an excess of near-side yield extending out in $\Delta\eta$ even after the most liberally measured elliptic flow contribution was subtracted (22). This excess yield, known as the “ridge” is clearly visible in Figure 9 (middle). The ridge was not something that was very well understood until recently. By

the late 2000s there was no shortage of theoretical models attempting to explain it. Many of these models relied on of some sort of jet-medium interaction. (23; 24; 25; 26; 27)

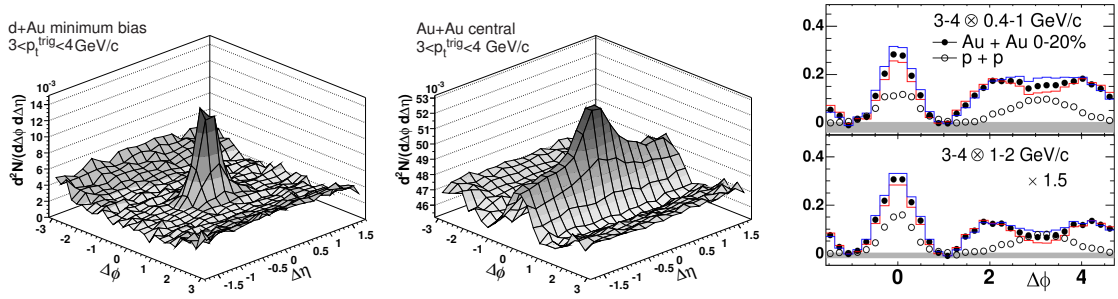


Figure 9. $\Delta\eta - \Delta\phi$ correlation for $\sqrt{s_{NN}} = 200$ GeV/c dAu (left) and central AuAu (middle) from the STAR Collaboration (22). $\Delta\phi$ correlation after v_2 subtraction showing the double-hump structure (right) from the PHENIX Collaboration (28).

Another surprise found in hadron correlation techniques was a strange structure that emerged in some kinematic ranges on the away side after the elliptic flow contribution was removed. The mysterious “double hump” structure in Figure 9 (right) inspired many a model and theory including the suggestion that the away-side structure might even be due to a mach-cone shock wave created as the away side high p_T parton traverses the medium. At the time these plots were published, the origins of the ridge and the double hump were unknown, and certainly not thought by most to be related to each other. It

turned out as will be explained in Section 1.8, that they were both in fact due to flow, but not elliptic flow.

1.8 Initial State Fluctuations

For central heavy ion collisions, one would not have expected to see a large elliptic-flow signal because the overlap region becomes circular as the impact parameter approaches zero. However, in 2006, the PHOBOS Collaboration (a RHIC experiment) found a substantial flow signal in the most central CuCu (copper-copper) collisions at both $\sqrt{s_{NN}} = 200$ GeV/c and at $\sqrt{s_{NN}} = 62.4$ GeV/c. This result was especially surprising because as the collisions became more central, elliptic flow measurements for AuAu collisions tended toward zero as expected. This raised the question of what could cause such a difference in flow signals between central CuCu and AuAu collisions when the overlap geometry is identical.

To answer this question PHOBOS sought to compare the flow signals from the two species directly, by first scaling out the difference in the initial geometric asymmetry of the collision, i.e., the eccentricity of the collision. Typically, eccentricity was calculated using a Glauber Monte Carlo with the assumption that the minor axis of the overlap ellipse is aligned with the reaction plane. This standard eccentricity is defined as,

$$\epsilon_{std} = \frac{\sigma_y^2 - \sigma_x^2}{\sigma_y^2 + \sigma_x^2} \quad (1.5)$$

where σ_x and σ_y are the RMS widths of the participant nucleon distributions projected on the x and y axes respectively.

PHOBOS also recognized that it was not enough to consider only the shape of the overlap region when calculating initial state anisotropies, as had been done previously (29). The colliding nucleons are lumpy, so to speak, so in principle, the created medium will also be lumpy. The random fluctuations in “lumpiness” can give rise to anisotropic flow signals. PHOBOS also considered the eccentricity of the participants themselves, with respect to an axis that is defined by eccentricity of the participants themselves, not the reaction plane. This was achieved by rotating the axes such that σ_x was minimized. Participant eccentricity, as it is now known, is defined as

$$\epsilon_{part} = \frac{\sqrt{\sigma_y^2 - \sigma_x^2 + 4(\sigma_{xy})^2}}{\sigma_y^2 + \sigma_x^2} \quad (1.6)$$

where $\sigma_{xy} = \langle xy \rangle - \langle x \rangle \langle y \rangle$. In AuAu collisions, ϵ_{std} and ϵ_{part} are quite similar for all but the most peripheral interactions. However for CuCu, the fluctuations in the nucleon positions in Glauber Model calculations become quite important for all centralities. The discrepancy between PHOBOS’ AuAu and CuCu data came from the fact that the 29 nucleons in copper created on average much more lumpy initial states than the 79 nucleons in gold. The study showed quite convincingly, as can be seen in Figure 10, that ϵ_{part} is the relevant quantity with regards to initial state anisotropy. The fact that v_2 divided by participant eccentricity lined up for all four sets of data points suggested that the initial

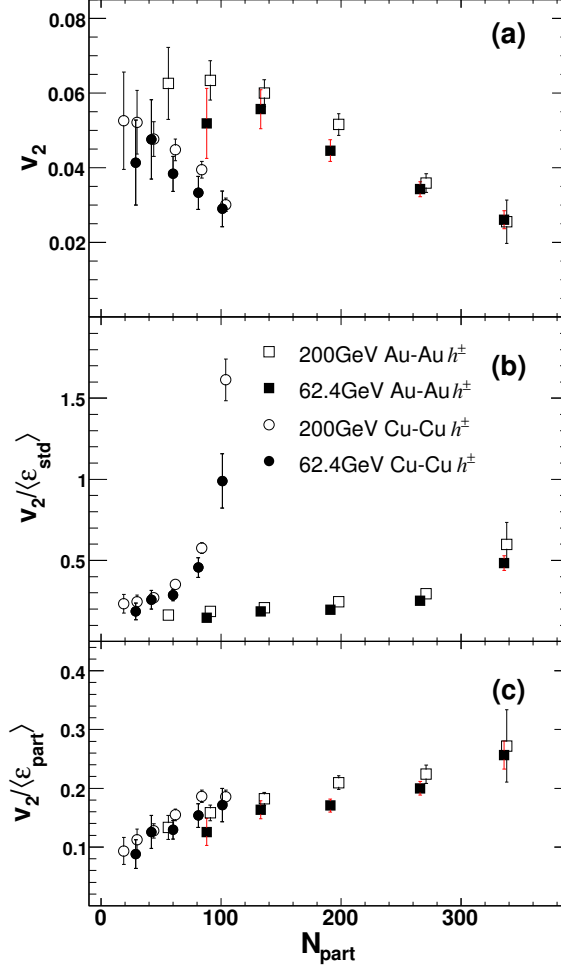


Figure 10. (a) v_2 for 200 GeV/c and 62.4 GeV/c AuAu and CuCu collisions. (b) v_2 divided by the average initial state eccentricity calculated in the standard way from the reaction plane. (c) v_2 divided by the average initial state eccentricity as calculated from the participant plane. The four sets of data points are unified.

state, governed by the geometry of the participants was more relevant than the initial state as predicted by the overlap region with regards to final state anisotropy (30).

The possibility of the most central CuCu collisions having a significant elliptic-flow signal regardless of the circular overlap region, opened the door for exotic lumpy initial state shapes to give rise to higher order flow terms as well. In 2010 the concept of triangular flow was introduced and found in Glauber Model calculations to contribute significantly to the two-particle correlation function (31). Triangular flow is characterized by the initial state “triangularity”, the 3rd order equivalent to eccentricity, given by

$$\epsilon_3 = \frac{\sqrt{\langle r^2 \cos(3\phi_{part}) \rangle^2 + \langle r^2 \sin(3\phi_{part}) \rangle^2}}{\langle r^2 \rangle} \quad (1.7)$$

where r and ϕ_{part} are the polar coordinate positions of the participating nucleons. Triangular flow contributes a $\cos(3\Delta\phi)$ term to the correlation function. If one looks back at Figure 9 in Section 1.7, one sees that an extra $\cos(3\Delta\phi)$ term would contribute both a near-side ridge, and an away-side double-hump structure qualitatively consistent with the features in the plots, which had previously been thought to be unrelated. It turns out that triangular flow is not quite enough to fully describe the ridge. However when one considers Fourier terms up to $n = 5$, the ridge’s exact shape and size is found to be consistent with what one would expect from flow given the initial state participant anisotropies within small uncertainties (18). The analysis in this thesis takes as a given that the ridge structure is due to flow alone.

CHAPTER 2

THE LHC AND THE CMS DETECTOR

2.1 The Large Hadron Collider

On December 8th, 2009, the Large Hadron Collider (LHC) at the European Center for Nuclear Research (CERN) first collided protons at $\sqrt{s} = 2.36$ TeV/c, besting the Tevatron's record of $\sqrt{s} = 1.96$ TeV/c. In November of 2010, the LHC saw the first heavy-ion collisions at $\sqrt{s_{NN}} = 2.76$ TeV/c, dwarfing RHIC's previous record of $\sqrt{s_{NN}} = 200$ GeV/c, marking a new era in heavy-ion physics.

2.1.1 LHC Layout and Machine Details

The LHC (32) is a two-ring superconducting hadron accelerator and collider straddling the border between Switzerland and France. It was installed in the pre-existing 26.7 km circumference tunnel that used to contain the CERN LEP machine. The LHC was designed to collide opposing particle beams of protons with an energy up to $\sqrt{s} = 7$ TeV/c, and lead nuclei (^{208}Pb) at $\sqrt{s_{NN}} = 5.5$ TeV/c. Over 10 000 scientists and engineers from hundreds of universities and laboratories residing in over 100 countries collaborated to build the LHC at CERN.

The basic layout of the LHC is presented in Figure 11. The LHC tunnel has eight sections, called octants, and lies between 45 m and 170 m below the surface. Each octant has a straight section approximately 528 m long which can be used for an experiment or a

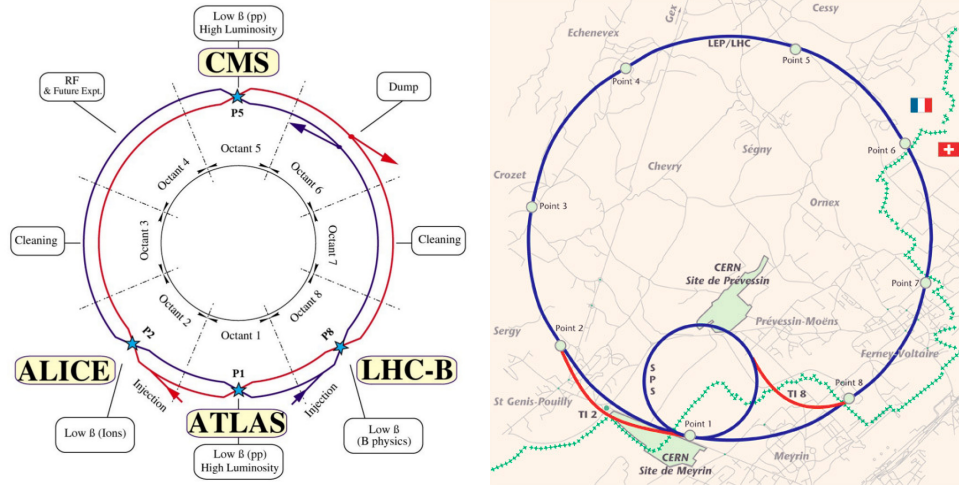


Figure 11. Schematic layout of the LHC with Beam 1 running clockwise and Beam 1 running counterclockwise. (left) The geographic location of the LHC Tunnel. (right)

utility insertion such as a beam dump, or cleaning mechanism. A “Point” corresponds to the point in an octant where the experiments are located. The ATLAS Experiment (33) and the CMS Experiment (34) are located at Point 1 and Point 5 respectively. ATLAS and CMS are two high-luminosity (peak at $\mathcal{L} = 10^{34} \text{ cm}^2\text{s}$) experiments, which both serve as general purpose detectors. Although they were primarily designed with proton-proton collisions in mind¹, both detectors are excellent heavy-ion detectors as well, and heavy-ion sub-collaborations consisting largely of former RHIC physicists have developed

¹Use of the CMS detector as a heavy-ion detector was actually considered from the very beginning (35).

and produced very important physics results in a short amount of time. Point 2 is the location of both the injection system for Beam 1, and the ALICE Experiment (36), which was designed with heavy ions in mind. The LHCb Experiment (37), designed to study the physics of b-quarks, as well as the injection system for Beam 2 is located at Point 8. ALICE and LHCb are both low luminosity (peak at $\mathcal{L} = 10^{32} \text{ cm}^2\text{s}$) experiments. Points 3 and 7 are host to collimation systems, while Point 4 hosts two radio frequency systems needed to capture, accelerate and store the two beams. The beam dumping system is located at Point 6. In addition, two small experiments were built at LHC: TOTEM (38), which is located next to CMS at Point 5 and LHCf (39), which is located next to ATLAS at Point 1. Their goal is to detect forward particles that do not participate in collisions.

A central feature of the LHC is the use of cutting-edge superconducting magnets to steer the beams. Magnetic fields and vacuum chambers for the two beams are separate, except in the interaction regions. The magnets are cooled to below 2 K with superfluid helium and provide a magnetic field of over 8 T.

Although the LHC was designed as a proton collider, heavy-ion collisions were included in the conceptual design from an early stage. With the nominal magnetic field of 8.33 T in the dipole magnets, fully stripped lead ions ($^{208}\text{Pb}^{82+}$) will have a beam energy of 2.76 TeV/nucleon (or 5.5 TeV/nucleon pair), yielding a total center-of-mass energy of 1.15 PeV and a nominal luminosity of $10^{27} \text{ cm}^2\text{s}^{-1}$. Collisions between ion beams were originally planned to be principally provided at Point 2 for the specialized

ALICE detector. However, because of the the development of the CMS and ATLAS Collaborations' heavy-ion programs, ion collisions are provided at Points 1 and 5 with similar luminosities.

2.1.2 Beam Luminosity

The luminosity is a quantification of the number of particles that cross a given area in a given time. It is a crucial parameter for the commissioning process and is needed for precise physics measurements. The instantaneous luminosity for a Gaussian beam distribution is given by

$$\mathcal{L} = \frac{N_p^2 N_b f_{rev} \gamma_r}{4\pi \epsilon_T \beta^*} F \quad (2.1)$$

where N_p is the number of particles per bunch, N_b the number of bunches in the beam, f_{rev} the revolution frequency, and γ_r the relativistic gamma factor. ϵ_T is the normalized transverse beam emittance, a measure of the spread of the particles. A low emittance reduces the likelihood of particle interactions, thus resulting in higher luminosity. β^* is the beta function at the collision point, which is also a measure of the spread in that it is roughly the square root of the maximum radius of the envelope that contains all the particles in the beam. F is the geometric luminosity reduction factor due to the crossing angle given by

$$F = \left(1 + \left(\frac{\theta \sigma_z}{2\sigma^*} \right)^2 \right)^{-1/2} \quad (2.2)$$

where θ_c is the full crossing angle at the interaction point, σ_z is the RMS bunch length, and θ^* is the transverse RMS beam size. These expressions assume round beams with $\sigma_z \ll \beta^*$.

Some aspects of the heavy-ion beam are similar to the proton beam setup. For example, the nominal emittance of the ion beam is chosen such that the ion beams have the same geometric size as the nominal proton beams (at beam energies corresponding to the same magnetic field in the dipole magnets). The physics of ion beams is quite different than that of protons, and thus the values of some parameters are necessarily very different. The nominal beam parameters of interest for protons and lead-ion beams are given in Table I.

TABLE I

LHC NOMINAL PARAMETERS FOR PROTON AND LEAD-ION COLLISIONS.

Beam Parameters	Protons	Lead Ions
Injection energy per nucleon [GeV]	450	177.4
Collision energy per nucleon [TeV]	7	2.759
Relativistic “gamma” factor γ_r	7460.5	2963.5
Number of ions per bunch N_p	1.7×10^{11}	7.0×10^7
Number of bunches per beam N_b	2808	592
Transverse normalized emittance ϵ_T [μm]	3.75	1.5
RMS bunch length σ_z [cm]	1.0	7.94
Beta function β^* [m]	1.0	0.5
Geometric luminosity reduction factor F	0.84	1
Maximum instantaneous luminosity [$\text{cm}^{-2}\text{s}^{-1}$]	10^{34}	10^{27}

2.1.3 Bunch Patterns and Collision Rates

It was expected that the LHC would collide protons with center of mass energy, $\sqrt{s} = 14$ TeV in 5 different bunch patterns over 5 the different luminosity ranges shown in Table II (40). The luminosity ranges cover 5 orders of magnitude.

TABLE II
BUNCH PATTERNS AND LUMINOSITY RANGES.

Bunch Pattern	Luminosity Range [$\text{cm}^{-2}\text{s}^{-1}$]
1 x 1	10^{27}
43 x 43	$3.8 \times 10^{29} - 6.1 \times 10^{30}$
156 x 156	$1.1 \times 10^{31} - 1.1 \times 10^{32}$
936 x 936	$2.3 \times 10^{31} - 5.0 \times 10^{32}$
2808 x 2808	$1.7 \times 10^{32} - 1.0 \times 10^{34}$

Because the probable number of collisions per bunch crossing scales linearly with luminosity for a given bunch pattern, the likely number of collisions per bunch crossing also varies greatly from 1 collision per 1000 bunch crossings, to 25 collisions in the same bunch crossing. In order to collect as much usable data as possible, a dynamic and efficient system for deciding when to read out the detector must be in place. This is called “triggering”.

As shown in Figure 12, there are regions of luminosity where the average number of pp collisions is approximately 1. In these regions it makes sense to simply read out the detector at every bunch crossing. In regions where the average number of collisions is much lower than 1, a triggering scheme has to be applied. It is in the interest of many physics analyses to have a triggering scheme that has the minimum possible influence on the data which is collected. Thus, a good minimum bias trigger that seeks to record all the physics events with as little noise as possible is essential to any detector. For the CMS detector (described in Section 2.2), 10 different potential minimum bias triggers for proton collisions at $\sqrt{s} = 14$ TeV were explored in 2007 using simulations, and their efficiencies were measured (40). The names of the triggers and their efficiencies are shown in Figure 13.

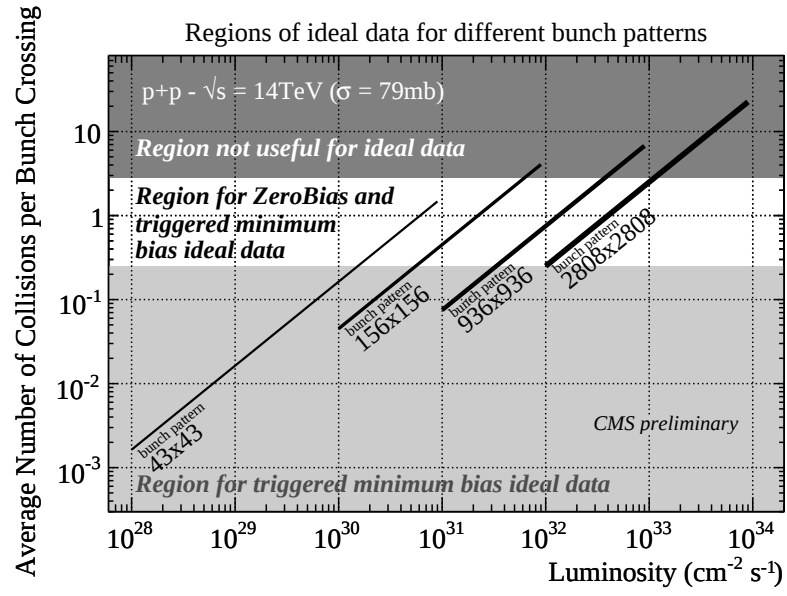


Figure 12. Average number of collisions per bunch crossing for four bunch patterns as a function of luminosity.

Assuming a heavy-ion collision to be the superposition of N_{part} pp events, a justifiable scaling given the evidence in Section 1.4, the lower limit of the heavy-ion efficiency as a function of the pp efficiency can be predicted using binomial statistics as follows. The probability of a heavy-ion collision triggering can be modeled as the probability of at least one of N_{part} pp collisions triggering, or rather one minus the binomial probability of zero out of N_{part} pp collisions triggering given by

$$P_{HI}(N_{\text{part}}, P_{\text{pp}}) = 1 - P_{\text{bin}}(0, N_{\text{part}}, P_{\text{pp}}) = 1 - (1 - P_{\text{pp}})^{N_{\text{part}}} \quad (2.3)$$

where P_{HI} is the probability of the heavy-ion event triggering, P_{pp} the probability of a pp event triggering, and $P_{\text{bin}}(0, N_{\text{part}}, P_{\text{pp}})$ the binomial probability of 0 out of N_{part} pp events with probability P_{pp} triggering. Figure 13 shows the binomially estimated PbPb triggering efficiency as a function of the pp efficiency estimated via simulations for 10 different potential triggers. Even with a relatively low pp efficiency, the efficiency for heavy ions is rather high.

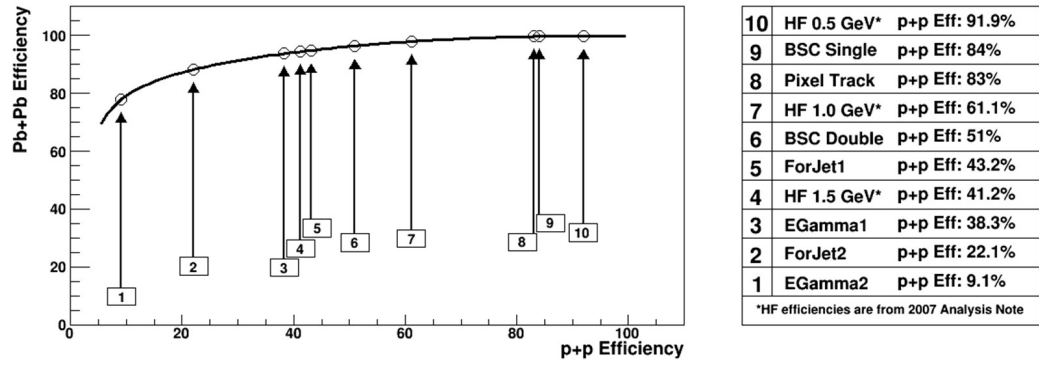


Figure 13. Binomially predicted heavy-ion efficiencies as a function of pp efficiency (left), and the names of ten potential minimum bias triggers and their corresponding pp efficiencies (right).

2.2 The Compact Muon Solenoid Detector

The Compact Muon Solenoid (CMS) detector (41) is an apparatus designed to meet the wide range of LHC physics program goals, specifically:

- Good muon identification and momentum resolution over a wide range of momenta and angles
- Good charged-particle momentum resolution and reconstruction efficiency in the inner tracker
- Good electromagnetic energy resolution, good di-photon and di-electron mass resolution, and efficient photon and lepton isolation at high luminosities
- Good missing-transverse-energy and dijet-mass resolution

The central features of the CMS detector, Figure 14, include its superconducting solenoidal magnet, silicon tracker, and electromagnetic calorimeter based on homogeneous scintillating crystals. The detector shown in Figure 14 weighs 12 300 metric tons, and measures 21 m long, 15 m wide, and 15 m high.

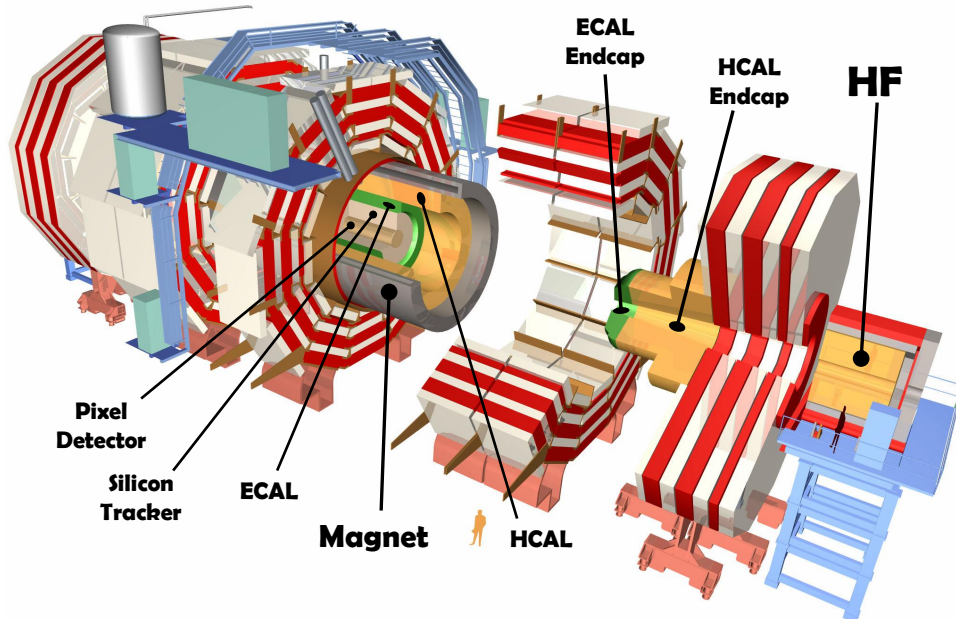


Figure 14. The CMS Detector with relevant subsystems indicated. The BSC and the ZDC are not pictured.

The detector uses a right handed x, y, z coordinate system with the x-axis pointing toward the center of the LHC ring and the y-axis pointing upwards. The azimuthal angle ϕ is measured counter-clockwise from the x-axis looking down on the xy plane from the positive z-axis. The polar angle θ is measured from the positive z-axis. Pseudorapidity, η , is preferred to θ due to its approximate boost invariance. It is defined as

$$\eta = -\ln \left(\tan \left(\frac{\theta}{2} \right) \right). \quad (2.4)$$

Figure 15 shows a transverse slice of the CMS detector. Particles emanating from the collision vertex pass first through the silicon tracker. Charged particles bend in the magnetic field, allowing for momentum measurement. Next are the calorimeters which measure the energy of the particles. The Electromagnetic Calorimeter (ECAL) measures the energy of photons and electrons, where the Hadronic Calorimeter (HCAL) is designed to measure the energy of hadrons. Finally the Muon system identifies muons.

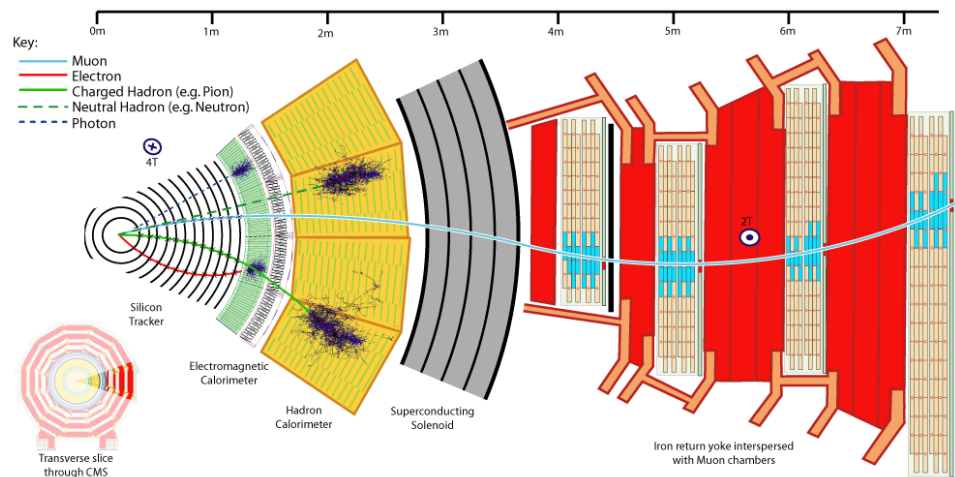


Figure 15. Transverse slice of the CMS detector showing the path of various particles as they travel from the collision point through the various sub-detectors.

The CMS magnet for which the detector is named, shown in Figure 16, is designed to reach a 4 T field with a stored energy of 2.6 GJ at full current. There is a 10 000 ton return yoke made of 5 wheels and 2 endcaps, each composed of three disks.

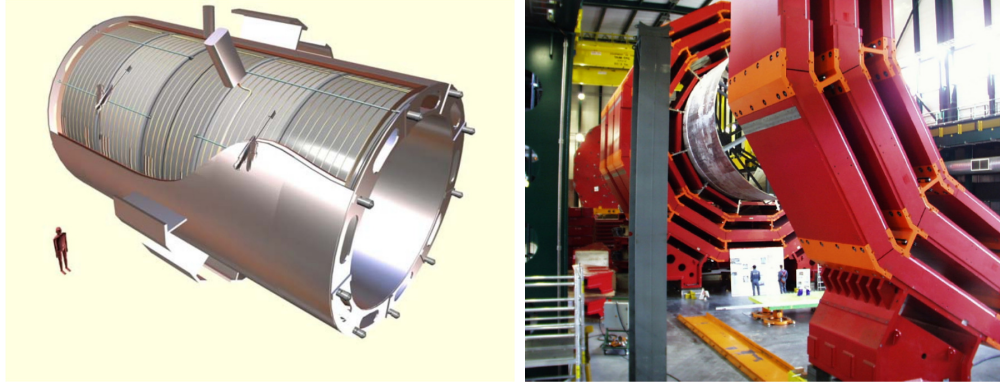


Figure 16. CAD drawing of the CMS Magnet coils (left) and photo of the return yoke (right).

The solenoid provides an approximately uniform magnetic field inside the coils. Immersed in the magnetic field are several sub-detectors: the pixel detector, the Silicon Strip Tracker (SST), the lead-tungstate crystal Electromagnetic Calorimeter (ECAL), and the brass-scintillator Hadron Calorimeter (HCAL). In addition to barrel and end-cap detectors for ECAL and HCAL, the steel-quartz-fiber Forward Hadronic Calorimeter (HF) covers the region of $|\eta|$ between 2.9 and 5.2. Muons are measured in gas-ionization

detectors embedded in the steel return yoke. The CMS subsystems relevant to this thesis are each described briefly in the sections that follow, with important features highlighted.

2.2.1 The Pixel Detector and the Silicon Strip Tracker

The CMS Tracker is named for its primary function, tracking. Tracking is the reconstruction of particle trajectories from the signals in the detector modules (playing connect-the-dots in 3D, so to speak). It is the momentum and direction of charged particles that are the core objects used in dihadron correlation techniques, thus the Tracker is at the heart of this analysis. All other parts of the detector mentioned here are needed only indirectly for data acquisition and triggering, cross checks and sanity checks, as well as the centrality determination. Once the data has been taken, cleaned, and verified, only the information from the Tracker (including the Pixel Detector) is needed (together with the centrality).

The inner tracking system of CMS is designed to provide a precise and efficient measurement of the trajectories of charged particles emerging from the LHC collisions. Another consideration in its design is the precise reconstruction of secondary vertices. It has a length of 5.8 m and a diameter of 2.5 m and surrounds the interaction point. There will be on average about 1000 particles from more than 20 overlapping proton-proton interactions traversing the Tracker for each bunch crossing, i.e. every 25 ns at the nominal design luminosity of $10^{34} \text{ cm}^2\text{s}^{-1}$. For this reason, it is important that the Tracker has

high granularity and fast response, such that the trajectories can be identified reliably and attributed to the correct bunch crossing.

To achieve these goals, the on-detector electronics require a high power density, which in turn requires efficient cooling. At the time of design, this posed a conflict with the goal of using a small amount of material to minimize multiple scatterings, bremsstrahlung, photon conversion and nuclear interactions. A compromise had to be found in this respect. The intense particle flux would cause severe radiation damage to the tracking system as well. In order to develop detector components able to operate in this harsh environment for an expected lifetime of 10 years, the Tracker design is based on silicon detector technology.

The Tracker consists of 1440 silicon-pixel and 15 148 silicon-strip detector modules and measures charged particle trajectories within the nominal pseudorapidity range, $|\eta| < 2.4$. The silicon-pixel detector (Pixel Detector) modules are comprised of the three innermost barrel layers of the Tracker, each 53.3 cm long, plus two end-cap disks on each side of the barrel section. The the three layers have radii of 4.4 cm, 7.3 cm and 10.2 cm.

The SST adds an additional 10 barrel detection layers to the Tracker extending outwards to a radius of 1.1 m, and is also completed by endcaps consisting of 3 plus 9 disks on each side of the barrel, extending the acceptance of the Tracker up to a pseudorapidity of $|\eta| < 2.5$.

The Tracker is designed to provide an impact-parameter resolution of about $100\ \mu\text{m}$ and a transverse-momentum (p_{T}) resolution of about 0.7% for $1\ \text{GeV}/c$ charged particles at normal incidence ($\eta = 0$) for pp collisions (41). Before the LHC turned on, extensive heavy-ion tracking studies for charged particles with $p_{\text{T}} > 0.8\ \text{GeV}/c$ were performed using the full GEANT4-based detector simulation package called OSCAR, and the reconstruction package called ORCA. Information about these packages can be found in (42; 43). Although there are some expected similarities between PbPb collisions and multiple pp collisions from the same bunch crossing, some differences arise from the fact that in a central heavy-ion collision, all the tracks will point back to the same vertex. According to these early studies, this leads mainly to a difference in algorithmic reconstruction efficiency, predicted to be around 75% , and rate of fake tracks (reconstructed by incorrectly connecting the dots), of around 5% for charged particles with $p_{\text{T}} > 1\ \text{GeV}/c$ (44). These predictions are consistent with the more recent results found in Appendix A. The tracking algorithm used in this analysis will be discussed in detail in Section 3.7.

Figure 17 shows a cross section of the tracker, and the sections it is composed of: the Pixel Detector, the Tracker Inner Barrel (TIB), the Tracker Inner Disks (TID), the Tracker Outer Barrel (TOB) and the Tracker Endcaps (TEC).

The TIB consists of the 4 barrel layers just outside the Pixel Detector and reaches a radius of $55\ \text{cm}$. It consists of silicon strips running parallel to the beam axis with a

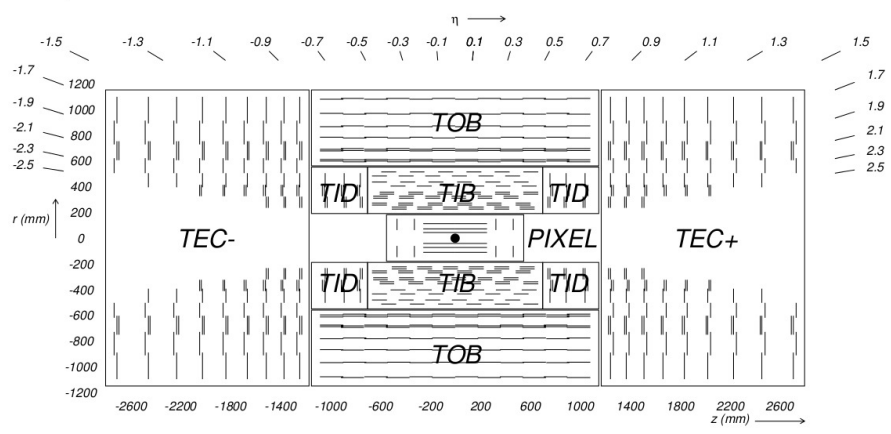


Figure 17. The CMS Tracker cross-section.

thickness of $320 \mu\text{m}$. Layers 1 and 2 have strips with a pitch of $80 \mu\text{m}$, while layers 3 and 4 have a pitch of $120 \mu\text{m}$. The single-point resolution for these layers is $20 \mu\text{m}$ in r , and $35 \mu\text{m}$ in ϕ .

The TID consists of 3 disks at each end of the TIB and is also composed of $320 \mu\text{m}$ thick silicon sensors. The strips are however arranged in a plane perpendicular rather than parallel to the beam axis. For the strips in the TID, the pitch ranges from $100 \mu\text{m}$ and $141 \mu\text{m}$ resulting in a resolution of $30 \mu\text{m}$ in z , and $40 \mu\text{m}$ in ϕ .

The TOB makes up the next 6 layers surrounding both the TIB and the TID, and extending out to $z \pm 118 \text{ cm}$, and r to 116 cm . The TOB's sensors are $500 \mu\text{m}$ thick and are parallel to the beam axis like in the TIB. Their pitch ranges from $183 \mu\text{m}$ in the

first four layers to $112\ \mu\text{m}$ for the outer two. They provide a single-point resolution of $35\ \mu\text{m}$ in r and $52\ \mu\text{m}$ in ϕ .

The two TECs are located on either side of the TIB, and also consist of silicon strips of thickness $320\ \mu\text{m}$. The strips are arranged perpendicular to the beam axis and have pitch ranging from $100\ \mu\text{m}$ to $141\ \mu\text{m}$. The single-point resolution in the TEC is $30\ \mu\text{m}$ in z and $40\ \mu\text{m}$ in ϕ .

2.2.2 Electromagnetic Calorimeter

One of the main design criteria of the CMS Electromagnetic Calorimeter (ECAL) is the capability to detect the decay of two-photon Higgs events. This requires a homogeneous, and hermetic crystal calorimeter. The ECAL is made of 61 200 lead tungstate (PbWO_4) crystals in a central barrel, and two 7324-crystal endcaps. Each endcap also has a pre-shower detector placed in front of it. The high density crystals have a short radiation length of $0.89\ \text{cm}$, and a small Moliere radius of $2.2\ \text{cm}$ which ensures that electrons and photons will deposit all of their energy in the ECAL before reaching the edge of the detector. The high density crystals allow for a detector which is fast, has fine granularity and is resistant to radiation.

The ECAL Barrel (EB) is made up of “super-modules” consisting of 1700 trapezoidal crystals. The crystals are $22 \times 22\ \text{mm}^2$ in front and $26 \times 26\ \text{mm}^2$ in the back. Their length of $230\ \text{mm}$ corresponds to just under 26 radiation lengths ($25.8\ X_0$) all but guaranteeing the stoppage of photons and electrons. A pair of avalanche photodiodes attached to each

crystal are used to amplify the scintillation light. The EB covers pseudorapidity out to $|\eta| < 1.479$.

The ECAL Endcaps (EE) cover the pseudorapidity range of $1.497 < |\eta| < 3.0$. Each endcap consists of two halves, called “dees”. Each dee holds 3662 crystals grouped together in 5 x 5 crystal “super-crystals.” The reason the number of total crystals is not divisible by 25 is that there are 18 special partial super-crystals on the inner and outer circumference. The EE crystals have a rear face cross section of 30 x 30 mm², a front face cross section of 28.62 x 28.62 mm² and a length of 220 mm which corresponds to just under 25 radiation lengths ($24.7 X_0$). Vacuum photodiodes equipped with a single gain stage amplify the scintillation light.

In front of the EE is the ECAL Pre-shower. It has two layers, one radiator and one silicon-strip sensor. It was designed to improve the position resolution for electrons and photons. It is 20 cm thick and covers pseudorapidity from $1.6 < |\eta| < 2.6$ and covers 3 radiation lengths.

2.2.3 Hadronic Calorimeters

The CMS detector’s hadron calorimetry system (HCAL) is of particular importance for the measurement of hadron jets and neutrinos as well as exotic particles. A longitudinal cross-section of the HCAL system is shown in Figure 18. The dashed lines represent fixed values in η . The hadron calorimeter barrel (HB) and endcaps (HE), and forward calorimeters (HF) surround the Tracker and the electromagnetic calorimeter. The HB

is radially situated between the electromagnetic calorimeter and the magnet coil ($R = 1.77 - 2.95$ m). This sets a hard limit on the amount of material which can be used to absorb the hadronic shower. For this reason, there is also an outer hadron calorimeter (HO) which sits outside the magnet coil. The HF is situated 11.2 m from the interaction point, uses a Cerenkov-based, radiation-hard technology, and covers a pseudorapidity of $3 \leq \eta \leq 5.2$.

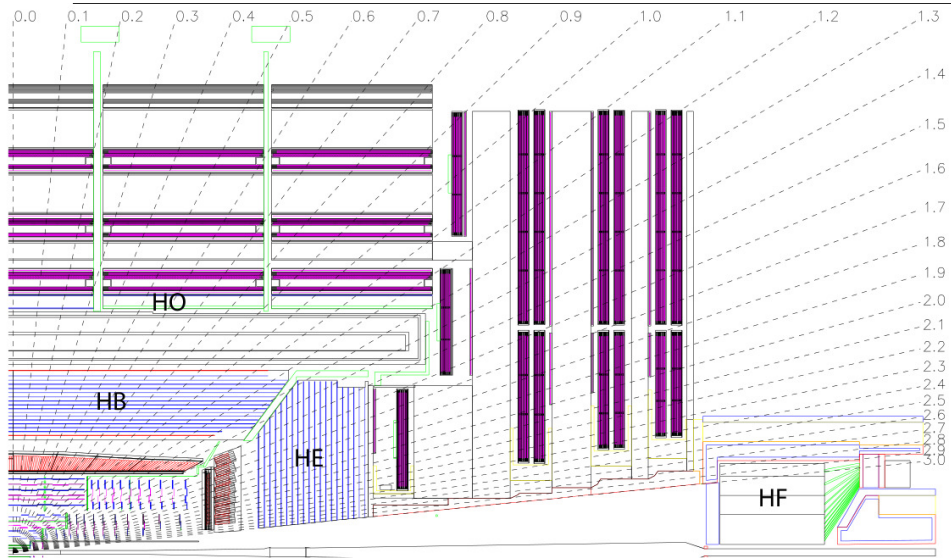


Figure 18. The HCAL cross-section.

2.2.4 Other Relevant Parts of the Detector

There is a set of two zero-degree calorimeters (ZDC) located roughly 140 m down the beam pipe in each direction from the main detector. They cover pseudorapidity $|\eta| \geq 8.3$ for neutral particles. The ZDCs consists of an electromagnetic section and a hadronic section. The hadronic sections are 24 layers of 15.5 mm thick tungsten plates tilted by 45° and 24 layers of 0.7 mm diameter quartz fibers. The electromagnetic section consists of 33 layers of 2 mm thick tungsten plates and 33 layers of 0.7 mm diameter quartz fibers. The combined depth is about 7.5 hadronic interaction lengths. They are designed such that the combined electromagnetic and hadronic calorimeters should allow for the reconstruction of spectator neutrons with energy 2.75 TeV with a resolution of 10-15%. This is useful in the measurement of heavy-ion centrality (see Section 3.5). In the 120 mm space between the calorimetric sections are the Beam Rate of Neutrals (BRAN) scintillators, which are used to measure the luminosity in real time.

Two elements of the CMS detector monitoring system, the Beam Scintillator Counters (BSCs) (41; 45) and the Beam Pick-up Timing for eXperiments (BPTX) devices (41; 46), were used to trigger the detector readout. The two BSCs are located at a distance of ± 10.86 m from the nominal interaction point and are sensitive in the $|\eta|$ range from 3.23 to 4.65. Each BSC is a set of 16 scintillator tiles. The BSC elements have a time resolution of 3 ns and an average minimum-ionizing-particle detection efficiency of 96.3%, and are designed to provide hit and coincidence rates. The two BPTX devices, located

around the beam pipe at a distance of ± 175 m from the interaction point on either side, are designed to provide precise information on the bunch structure and timing of the incoming beam, with better than 0.2 ns time resolution.

The detailed Monte Carlo (MC) simulation of the CMS detector response is based on GEANT4 (42). The position and width of the beam spot in the simulation were adjusted to that determined from the data. Simulated events were processed and reconstructed in the same manner as collision data.

CHAPTER 3

THE ANALYSIS

3.1 Detector Calibration

During the data taking period, 98.4% of the pixels and 97.2% of the silicon-strip channels were operational. The fraction of noisy pixel channels was smaller than 10^{-5} . The signal-to-noise ratio in the silicon strips is dependent on the thickness of the particular sensor, and ranges from 36 to 38, which is consistent with the design expectations and cosmic-ray measurements (47; 48). The tracker was aligned using cosmic-ray data prior to the commissioning of the LHC as described in (49).

3.2 Event Selection

The CMS triggering system consists of two levels of online event selection. The Level One (L1) trigger is the first to see the data, and consists of simple algorithms based on fast readout channels. It is followed by the High Level Trigger (HLT), which is used for more sophisticated triggering algorithms.

After an event is accepted by the L1 trigger, the pixel detector imposes a relatively long hold-off time of 100–300 microseconds¹, depending on the run/date, and on the triggering strategy. Another relevant constraint on data taking is the rate imposed by the

¹This is not the case for pp events, where occupancy of the pixel detector is much lower.

sheer volume of data produced by the Silicon Strip Tracker when read out in “Virgin Raw” operating mode, which means no zero-suppression, or that every data channel is read out regardless of how low the signal¹. This leads to storage limitations downstream. When these factors are added together, they lead to a collision rate limitation of about 150 Hz of physics events which can be recorded. The hadronic collision rate varies between 1 Hz and 210 Hz, depending on the bunch scheme (between 1×1 and 113×113) and varying bunch intensities. Thus, the L1 trigger system has to provide a very efficient and clean trigger for hadronic collisions, with no or moderate (2 or 3) prescale for minimum bias events, and no prescale for high- p_T jets, muons, or photons, combined with a High Level Trigger (HLT) using L1 pass-through paths in many cases. The HLT also prescales certain triggers for various data streams to separate the most interesting events and the bulk of minimum-bias collisions (in the interest of quick subsequent access to the “Core Physics” data set), and filtering and refining some of the L1 decisions, jet reconstruction, etc.

3.3 Types of Collisions and Available L1 Triggers

The CMS apparatus has at its disposal a diverse selection of triggers for PbPb collisions. At Level One (L1), The BPTX, HCAL, ECAL, HF, ZDC, BSC, and BRAN scintillators all provide information that can be combined in various ways to make the decision to pass an event to the High Level Trigger (HLT).

¹The detector was only read out in Virgin Raw mode for the 2010 heavy-ion run. This was because it was unknown how low the zero suppression thresholds could be set in a heavy-ion environment without losing data.

The hadronic inelastic cross section in 2.76 TeV PbPb collisions is 7.65 barns according to standard Glauber model estimations. For ultraperipheral collisions (UPC) with large impact parameters, where the breakup of one, or both, Pb nuclei occurs, the probability is much larger. In fact, the cross section is more than 200 barns for processes leading to one or more neutrons in one ZDC, and the cross section for ZDC coincidence is almost twice the hadronic interaction rate. Collisions with hadronic interactions between Pb nuclei can produce anywhere from just a few particles per unit pseudorapidity, to about 1600 particles per unit pseudorapidity (the multiplicity depends largely on the impact parameter). As a result, more than 97% of PbPb collisions trigger coincident (both plus and minus sides) signals in both the BSC and HF calorimeters.

These events also tend to set off a plus-minus coincidence trigger in the ZDC and in the BRAN scintillators located behind the ZDC electromagnetic section. In order to suppress non-collision related noise, cosmics, radioactivity, trigger afterglow and beam background, CMS requires a BPTX coincidence, i.e., there must be two colliding ion bunches at the time of triggering.

During the PbPb data-taking period, the collision rate was 1–1.85 Hz per colliding bunch pair. This, along with the 11 245 Hz orbit frequency, implies the average number of collisions per bunch crossing was $0.9 - 1.6 \times 10^{-4}$.

Unlike nuclear interactions, UPC events are found not to set off the HF and BSC coincidence triggers. However, they contribute significantly to both coincidence and

single side ZCD triggers and signals in the BRAN scintillators. The additional trigger rate from the coincidence triggers due to UPC events is comparable to that of hadronic collisions, and the single side rates (which have very low or no noise) are more than an order of magnitude higher than the hadronic collision rate.

For this reason, the BSC and HF coincidence triggers are used to select hadronic PbPb collisions. These triggers have low noise rates of less than 1 Hz for two non-colliding beams at full intensity with 121 bunches, and they have very high efficiency of about 97% even after an additional reconstructed vertex requirement is imposed.

The minimum bias (hadronic inelastic) collisions recorded in the 2010 heavy-ion run were selected by the L1 trigger system based on the above information. The BSC coincidence “threshold 1” trigger, which requires that at least one segment fired on each side of the interaction point, was one of two highly efficient triggers used. The BSC consists of 16 segments on each side (a total of 32 segments), out of which 31 were operational during the run. 75% of the collisions illuminated all 31 segments, thus the effect of the one dead channel on the overall trigger efficiency and bias was negligible. This trigger known colloquially as “L1 Algorithm 4”, corresponds to an L1 bit named “L1_BscMinBiasThreshold1_BptxAND”. It was used as the minimum bias trigger up to (and including) Run 150 593, i.e., until November 10, 2010, 11:38 AM UTC.

At this time, the minimum bias trigger was changed to a combination of the “L1_HcalHf-CoincPmORBscMinBiasThresh1_BptxAND” bit known as “L1 Algorithm 126”, and the

“L1_HcalHfCoincPmORBscMinBiasThresh1_BptxAND” bit, which is the Level-1 OR combination of the above L1_BscMinBiasThreshold1_BptxAND, and the “L1_HcalHfCoincidencePm_BptxAND” bit known as “L1 Algorithm 94.” The latter trigger bit requires energy deposited in at least two HF towers in excess of the threshold set in the firmware. Its efficiency is similar to the BSC coincidence, and it is also noise free. It does however catch some collisions that the previous trigger misses, contributing to a small increase in efficiency and trigger rate for minimum-bias collisions. This second minimum-bias trigger is also more consistent with (but less strict than) the offline event selection, which also relies heavily on the HF. In the event that either the BSC or the HF detector were to develop a problem (massive BSC damage or HF High Voltage turn-off for example), the “OR” allows

L1_HcalHfCoincPmORBscMinBiasThresh1_BptxAND to continue to record minimum bias collisions. Fortunately, such difficulties did not occur during data taking. This trigger has more than 97% acceptance for hadronic inelastic collisions.

The minimum-bias trigger was unprescaled at L1 level before reaching about a 60 Hz collision rate, and then it was prescaled by a factor of 2 or 3, depending on the collision rate, to keep data taking around the 150 Hz total HLT physics trigger limitation. There is no strict limit to the rate of data taking. However, when a rate closer to 200 Hz is attempted, some events are skipped and the rate of data actually recorded slows down

due to back pressure in the data streams. It is really a game of optimization in the control room using the prescale factors.

The HLT passed all of the minimum-bias events through to the “All Physics” data stream, although prescaled. The Core Physics data stream received these events prescaled again by a factor of 10, along with unprescaled jet, muon, and UPC triggered events.

3.4 Offline Event Selection

In order to clean background, beam gas, beam scraping (PKAM¹) and UPC events from the minimum bias events, a few more event selection cuts must be applied offline. These cleaning cuts have a very small effect on the final number of selected events.

First is the BSC halo filter. Events where any of the BSC halo bits fired (L1 Technical Trigger bits 36, 37, 38 or 39) were excluded from the analysis. These bits can be understood by looking at Figure 19, which shows the correlation between the number of hits in the first pixel layer and the total energy deposited in the HF. Collisions passing all offline event selections (colored points) have a very tight correlation between these two quantities. However, events that fire the BSC beam halo bits have relatively small HF energy compared to their number of pixel hits (black points near the vertical axis). These are excluded from the analysis.

¹This rather strange abbreviation actually stands for “Previously Known As Monster.” Due to the enormous occupancy of the detector in these events, it became fashionable to refer to them as “Monster” events. However, CMS management thought better of allowing this term to be used publicly, so the name was changed to PKAM.

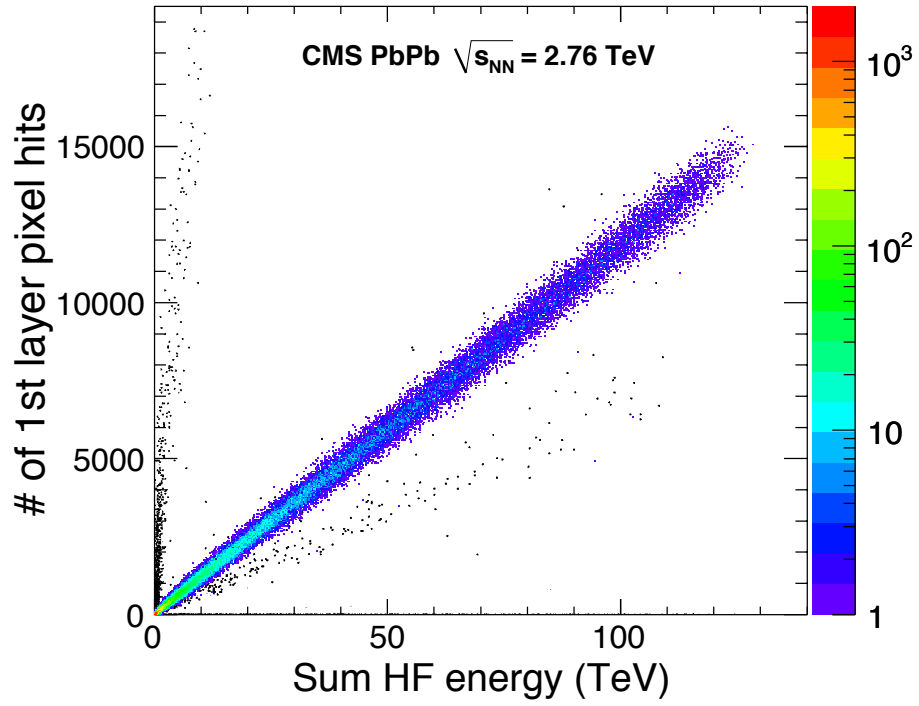


Figure 19. Correlation for minimum bias events between the number of pixel hits and the total energy deposited by the HF. Good collisions (colored points) have a tight correlation, while events firing the BSC halo bits, displaying PKAM-like features, or lacking a valid reconstructed vertex are off-diagonal.

A second offline filter is the requirement of a reconstructed 2-track primary vertex. All tracks above 75 MeV/c transverse momentum were used to reconstruct the vertex for peripheral events. In central events, the requirement for the minimum p_T was increased, and the tracking region narrowed, to keep the maximum number of fitted tracks stable at around 40–60. This helped to ensure time-efficient reconstruction. These requirements remove non-inelastic-collision events (e.g., beam-gas, UPC) with large HF energy deposits but very few pixel hits (black points along horizontal axis in Figure 19). The event vertex was also required to fall within a cylinder defined by a length of 15 cm, centered at the nominal collision point along the beam axis, and a radius of 0.02 cm measured perpendicular to the beam relative to the average XY vertex position. As will be explained in Section 3.9, the analysis was performed in small z-vertex position bins. Outside this relatively narrow vertex range of 15 cm, the density of events was relatively small, and good statistics for constructing a mixed-event background distribution within the narrow vertex bin could not be ensured, thus events with vertex falling outside this cylinder were ignored. The vertex distributions in z and x-y direction are shown in Figure 20.

Next a cut to remove PKAM events was introduced. Specifically, a requirement on pixel cluster-length compatibility with the vertex was applied. This cut was identical to what was described in the first 7 TeV pp paper on $dN/d\eta$ and dN/dp_T (50). As shown in Figure 19, most background events which have an excess of pixel hits in comparison to the HF energy have been caught by the BSC beam halo filter described above. However,

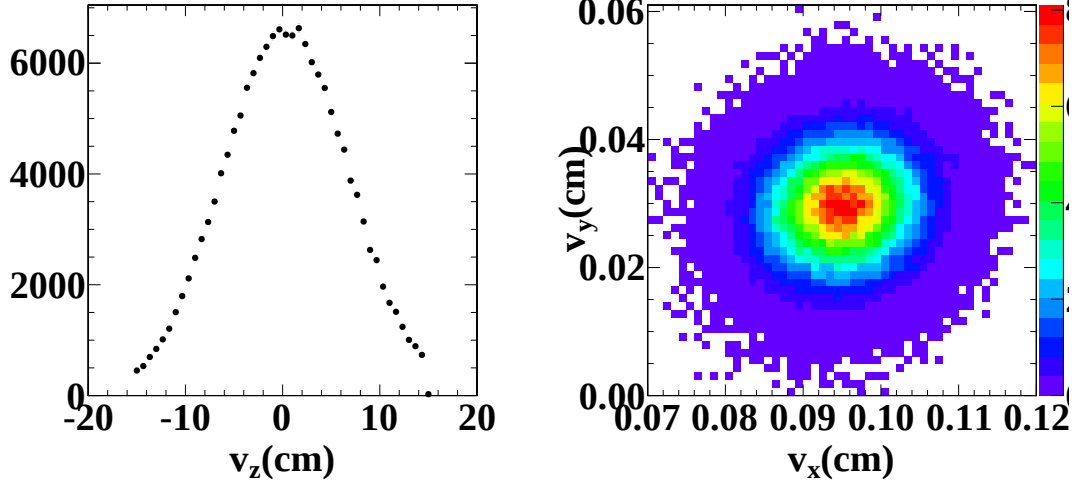


Figure 20. v_z (z-vertex) and v_x - v_y distributions for the 0-5% most central PbPb data.

the combination of the halo filter and the PKAM cut ensures that all such background events are removed. Figure 21 shows the cluster-vertex compatibility as a function of pixel hit multiplicity. The compatibility variable is the number of clusters that have a length (in the global z direction, i.e., along the beam) that is compatible with the reconstructed vertex, divided by the number of hits that are compatible with an artificially displaced vertex position (offset by ± 10 cm). If this ratio is high, that indicates a well defined vertex and a valid collision. If the ratio is 1, that indicates that the vertex is ill-defined, a characteristic feature of PKAM events. At very low values of pixel multiplicity, the compatibility is allowed to be low, in order to keep events that may have a larger background hit fluctuation, but are otherwise good collisions. The cut, shown by

the red line in Figure 21, is meant to remove events with a high number of pixel hits and a low value of the compatibility variable. The right panel is the same as the left panel, but zoomed in to the low-pixel multiplicity region.

Finally, the requirement of an off-line HF coincidence was imposed. Specifically, at least 3 towers on each side of the interaction point in the HF with at least 3 GeV total deposited energy must be triggered.

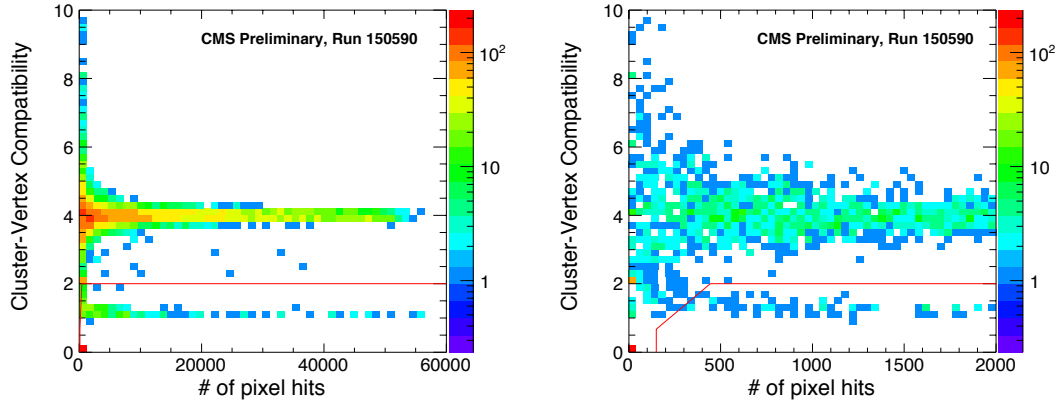


Figure 21. The so-called "monster" (or PKAM) cut. Events with a large number of pixel hits (horizontal axis) but a small value of the calculated measure of compatibility between the vertex position and the cluster lengths (vertical axis) are eliminated from the analysis (i.e., those events that fall below the cut shown by the red line.). The right panel is an expanded version of the bottom left of the left panel.

A total integrated (PbPb) luminosity of $7.36 \mu\text{b}^{-1}$ was collected, of which $3.92 \mu\text{b}^{-1}$ was included in this analysis, corresponding to 3 343 934 minimum bias PbPb collisions after all event selections were applied.

3.5 Centrality Determination

CMS determines centrality using the total sum of energy signals from both the positive and negative HF (covering $2.9 < |\eta| < 5.2$). The quantity used is total energy rather than E_T . The distribution of the HF signal used in this analysis is shown in Figure 22.

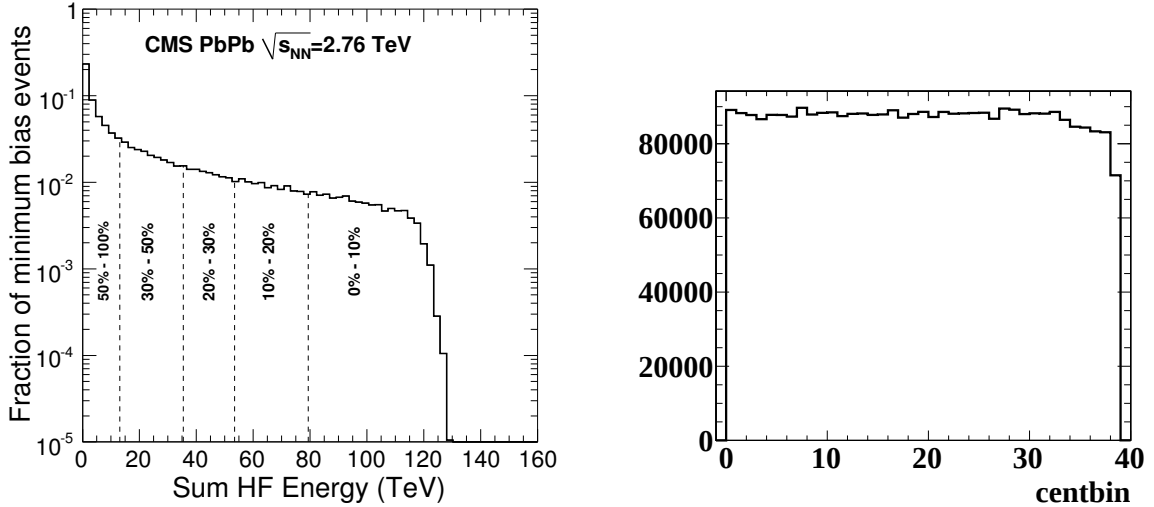


Figure 22. Probability distribution of the total HF energy for minimum bias collisions (left). Five arbitrary centrality percentiles are marked. Distribution of the events in the 40 centrality bins for minimum bias events (right). The centrality-bin labels run from 0 for the most central to 40 for the most peripheral events.

The shape of the energy distribution is typical for observables that are related to soft-particle production in heavy-ion collisions. The peripheral events with large impact parameter produce very few particles, however, they are much more frequent. The central events with small impact parameter produce many more particles due to the increased number of nucleon-nucleon interactions.

This distribution of total HF energy is used to divide the events into 40 centrality bins, each representing 2.5% of the total number of events. Figure 22 also shows the centrality bin distribution. Bin 0 corresponds to the most central collisions. The centrality bin distribution is virtually flat all the way out to bin 33, where it then starts to taper off due to centrality-biased (multiplicity-biased) triggering inefficiency. This analysis only considers the top 80% central events and is therefore not affected by this bias.

Because of inefficiencies in the minimum bias trigger and event selection, the measured multiplicity distribution does not represent the full interaction cross section. MC simulations were used to estimate the distribution in the regions where events are lost. Comparing the simulated distribution to the measured distribution, it is estimated that the minimum bias trigger and event selection efficiency is $97 \pm 3\%$. This loss is however irrelevant to this analysis as it is not concerned with total cross-sections, only statistical per-event yields.

The centrality bins are correlated with the impact parameter, b , and to the average values and variances of N_{part} and N_{coll} using a Glauber Monte Carlo simulation in which

the nucleons are assumed to follow straight-line trajectories as the nuclei collide (see Section 1.3). The nucleon-nucleon inelastic cross section, which indicates the minimum center-to-center distance for the nucleon trajectories needed for an interaction to occur, was taken to be 64 ± 5 mb, based on a fit of existing data for total and elastic cross-sections in proton-proton and proton-antiproton collisions (51).

3.6 Data and Monte Carlo Samples

The centrality dependence of the 2010 data set for PbPb collisions at $\sqrt{s_{NN}} = 2.76$ TeV was performed using the full PbPb data recorded by CMS that were certified by the Physics Validation Team (PVT) using CMS software version CMSSW_3_9_9_patch1. The first step in the data preparation was the re-reconstruction of the “All Physics” data stream with the “Improved Tracker Zero Suppression” algorithm. Good collision runs and luminosity blocks were selected using the official JSON file that was signed off on by the PVT, corresponding to a total sampled integrated luminosity of $3.9 \mu\text{b}^{-1}$.

100K Minimum bias HYDJET PbPb Monte Carlo samples, simulated using the same detector conditions as the real data in software version CMSSW_3_9_3 were the primary MC samples used to correct the detector effects, tracking efficiency, etc. For model comparisons, AMPT PbPb MC at $\sqrt{s_{NN}} = 2.76$ TeV and PYTHIA8 were used at the generator level. The generator samples were produced privately, without any CMS detector simulation. A summary of official data and MC samples is shown in Table III.

TABLE III

OFFICIAL DATA AND MC SAMPLES.

Data	/HIAllPhysics/HIRun2010-ZS-v2/RECO
MC	/Hydjet_Bass_MinBias_2760GeV/Fall10-START39_V7HI-v1/GEN-SIM-RECODEBUG

3.7 Tracking

Tracking is the reconstruction of particle trajectories from the hits recorded by the detector. For the 2010 heavy-ion collision data, two tracking algorithms were used, and the results were merged. This was necessary to efficiently and cleanly reconstruct tracks across a broad range of p_T . In the first algorithm, tracks were seeded with pixel detector triplets, then propagated through the silicon strip detector using a combinatorial Kalman filter, a recursive Bayesian estimator. Predictions for the true path of the particle are made iteratively in discrete steps. At each step the trajectory model is updated with the matching detector hits. This algorithm and general method of tracking is common to both proton-proton and lead-lead analyses in CMS.

These tracks which will be referred to here as “full tracks”, have a low fake rate and reasonable efficiency at transverse momenta above 1.5 GeV/c. A second track reconstruction algorithm was also implemented using only the hits in the pixel detector, but with the beam-spot as an additional constraint. These pixel-only tracks have a reasonably low fake rate and decent momentum resolution below 1.8 GeV/c. In this analysis, tracks

with p_T above 1 GeV/c are considered, and thus both collections are needed, however most of the tracks are full tracks from the first algorithm.

The full-track algorithm consists of the following four steps:

(1) Reconstruction of the primary vertex: First, a rough estimate of the z-vertex position is obtained by maximizing the compatibility of the pixel cluster lengths and global z-positions with a primary vertex hypothesis. This 1-d vertex position, with approximately 1 mm accuracy, is used to loosely constrain the origin of the tracking region used to make a first round of pixel triplet “proto-tracks.” The number of these proto-tracks is kept around 40-60 even in the highest occupancy events by successively restricting the eta-phi extent of the tracking region as a function of pixel multiplicity. A selection of these pixel proto-tracks, originating from near the beam-spot transverse position and the median z position, are passed to the 3-d adaptive vertex fitter.

(2) Building the pixel triplet seeds: Based on the primary vertex fitted from pixel proto-tracks in the previous step, a new vertex-constrained global tracking region is defined with minimum $p_T = 0.9$ GeV/c, origin radius = 0.1 cm, and half-length = 0.2 cm. These pixel triplet seeds are fitted with the standard software module called PixelFitterByHelicalProjections, filtered based on χ^2 , required to point back to the primary vertex, and cleaned against each other based on shared hits. Pixel triplets sharing two hits are merged to produce four-hit seeds often enough to match the proportion expected from the geometry of overlapping pixel modules.

(3) Building and fitting the full-track candidates: Pixel triplet seeds are used to propagate trajectory states successively through the layers of the tracker without grouping overlapping strip layers. The five best trajectories are kept at each step and propagated to the next layer. The final collection of trajectories is filtered to contain only those with a minimum of 6 hits. Cleaned trajectories are finally passed to a fitter with outlier rejection.

(4) Selecting quality tracks:

To maximize the purity of the track sample, the following cuts were applied in the end to the collection of full tracks:

- Number of Valid Hits ≥ 12
- $dz / \sigma_{dz} < 3$
- $dxy / \sigma_{dxy} < 3$
- $p_T^{error} / p_T < 0.05$

Here dz is the longitudinal distance of closest approach of the track to the reconstructed vertex, and σ_{dz} is the error in dz for the track added in quadrature to the error in longitudinal position of the vertex. dxy and σ_{dxy} are calculated in a similar manner for the transverse distance of closest approach. For details of the tracking performance (efficiency and fake rate), see Appendix A.

3.8 Systematic Uncertainties

What follows in this section is a comprehensive study of the systematic uncertainties in the analysis for the 0–5% most central collisions. The most significant contributions to the systematic uncertainty are from the tracking performance. Since tracking is expected to be better in peripheral bins where the particle density is much lower than central collisions, the systematic errors found in the in-depth study of the 5% most central collisions are extended to all centrality bins as a conservative approach.

Table IV summarizes different sources of systematic errors and their sum in quadrature. All sources of errors are independent of $\Delta\eta$ and $\Delta\phi$, thus affect only the overall scale of the data points.

TABLE IV
SUMMARY OF SYSTEMATIC UNCERTAINTIES.

Source	Systematic Uncertainties
Semi data-driven tracking efficiency	5.0%
Tracking correction closure test	3.3%
Track selection dependence	2.0%
Vertex dependence	2.2%
Total	6.7%

Semi data-driven tracking efficiency:

The dominant source of systematic uncertainty in this analysis is from the performance of the tracking in the high multiplicity heavy-ion collision environment. Embedding simulated tracks into real events can provide a semi data-driven cross check of the tracking efficiency derived from pure MC.

Figure 23 shows the results of a study of the tracking efficiency where pyquen pt80 dijet MC signal samples were embedded into both minbias data and HYDJET MC. The agreement between the two samples is at least 5%, which is the number quoted in the systematic errors in Table IV.

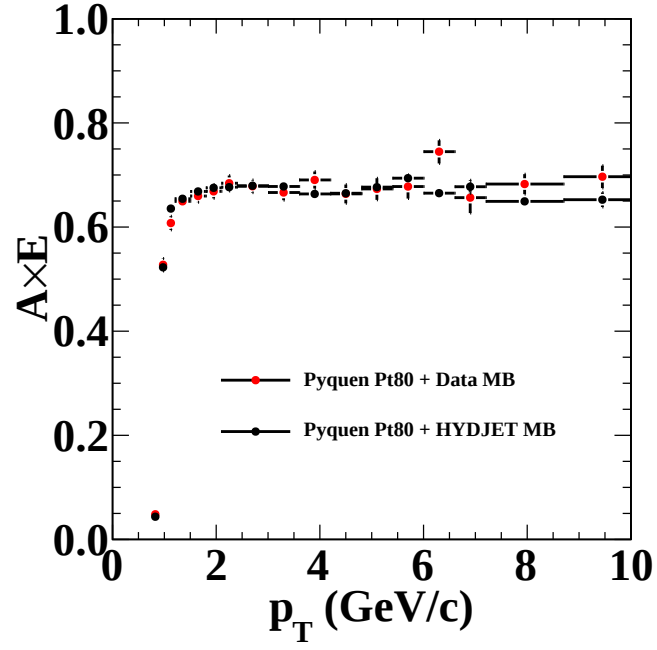


Figure 23. Tracking efficiency for $|\eta| < 1$ derived by embedding pyquen pt80 dijet MC signal into minbias data and HYDJET MC respectively.

Tracking efficiency correction closure test:

In order to validate the tracking efficiency weighting corrections which will be described in Section 3.9, a closure test of the efficiency correction was performed. Figure 24 shows the comparison of 1D projected $\Delta\phi$ correlation functions from the 0-5% most central HYDJET events for $4 < p_{\text{T}}^{\text{trig}} < 6$ GeV/c and $2 < p_{\text{T}}^{\text{assoc}} < 4$ GeV/c between the generator level, the reconstructed level before correction and the reconstructed-level after corrections. The ratio of the 1D azimuthal dihadron correlation functions (which will also be described in Section 3.9, projected over $0 < \Delta\eta < 1.0$, $1.0 < \Delta\eta < 2.0$ and $2.0 < \Delta\eta < 4.0$ between reconstructed-level after tracking efficiency correction and generator-level are shown in Figure 25. After corrections are applied, the generator-level and reconstructed-level results agree within about 3-4% as shown in Figure 24. This discrepancy of about 3.3% on average is to be taken as another source of systematic uncertainties and is quoted in Table IV.

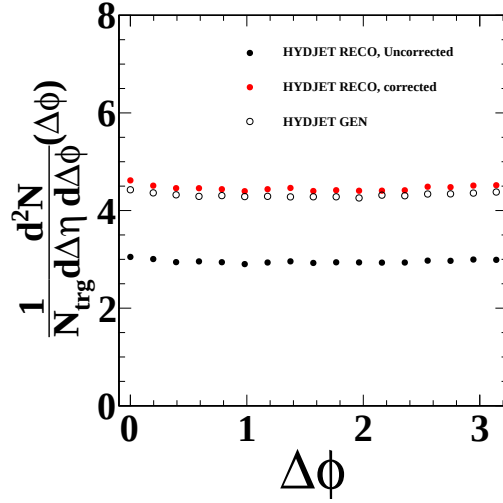


Figure 24. Comparison of 1D azimuthal dihadron correlation function in 2.76 TeV 0-5% central HYDJET projected over $0 < \Delta\eta < 4.0$ between generator-level, reconstructed-level before and after tracking efficiency correction for $4 < p_T^{\text{trig}} < 6$ GeV/c and $2 < p_T^{\text{assoc}} < 4$ GeV/c.

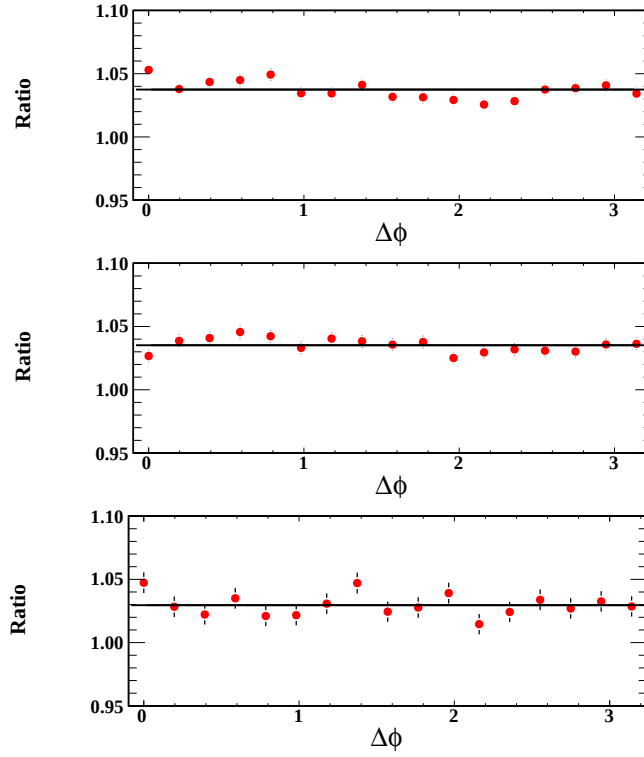


Figure 25. Ratio of 1D azimuthal dihadron correlation function in 2.76 TeV 0-5% central HYDJET projected over $0 < \Delta\eta < 1.0$ (top), $1.0 < \Delta\eta < 2.0$ (middle) and $2.0 < \Delta\eta < 4.0$ (bottom) between reconstructed-level after tracking efficiency correction and generator-level for $4 < p_T^{\text{trig}} < 6$ GeV/c and $2 < p_T^{\text{assoc}} < 4$ GeV/c.

Dependence on track-selection cuts:

As shown in Appendix A, the fake track at high η can blow up to almost 10%. By varying the track selection cuts, different efficiencies and fake rates can be achieved. By comparing the results after corrections among various track selections, systematics on tracking performance can be evaluated.

A set of looser cuts and a set of tighter cuts were chosen as follows:

Looser cuts:

- Number of Valid Hits ≥ 8
- $dz/\sigma_{dz} < 5$
- $dxy/\sigma_{dxy} < 5$
- $p_T^{error}/p_T < 0.1$

Tighter cuts:

- Number of Valid Hits ≥ 12
- $dz/\sigma_{dz} < 2$
- $dxy/\sigma_{dxy} < 2$
- $p_T^{error}/p_T < 0.05$

Figure 26 shows the comparison of 1D projected $\Delta\phi$ correlation functions over $0 < |\Delta\eta| < 4.0$ from the 0-5% most central PbPb data for $4 < p_T^{\text{trig}} < 6$ GeV/c and $2 < p_T^{\text{assoc}} < 4$ GeV/c between standard, looser (left) and tighter (right) track selections

after corrections are applied. The ratios of looser and tighter selections to the standard selections are shown in Figure 27. The largest variation among the different sets of track selections is about 2.0%. This is quoted as another source of systematic uncertainties in Table IV.

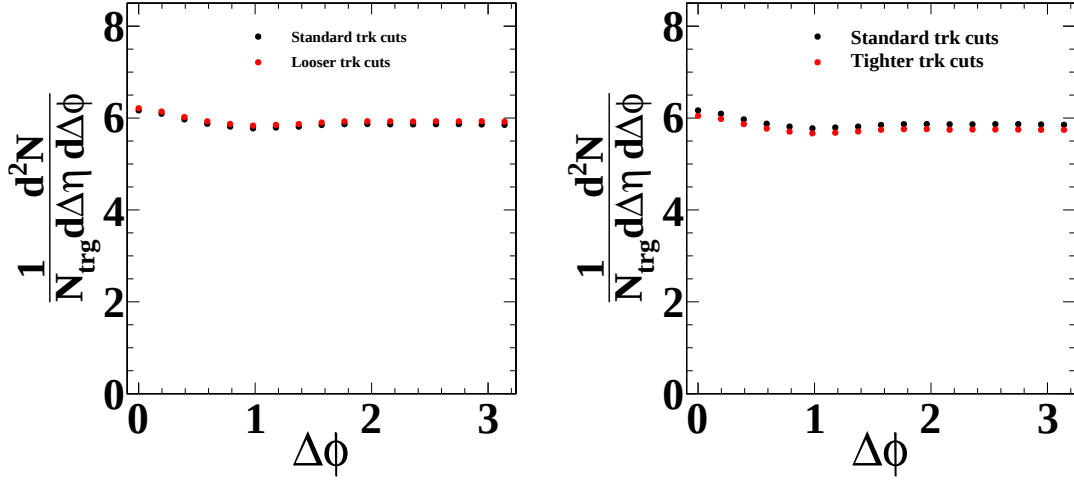


Figure 26. Comparison of 1D projected $\Delta\phi$ correlation functions over $0 < |\Delta\eta| < 4.0$ from the 0-5% most central PbPb data for $4 < p_T^{\text{trig}} < 6$ GeV/c and $2 < p_T^{\text{assoc}} < 4$ GeV/c between standard, looser (left) and tighter (right) track selections after corrections are applied.

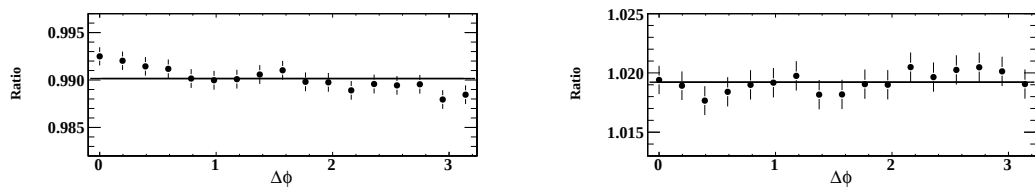


Figure 27. Ratio of looser (left) and tighter (right) selections to the standard selections.

Vertex dependence:

The tracking efficiency correction is calculated individually for each vertex bin, however, due to limited MC statistics it is then averaged over the entire z vertex range of $|z_{vtx}| < 15$ cm. In principle, the final analysis results should be independent of the vertex range used in the analysis. In Figure 28, the ratio of tracking efficiency correction factor for $|z_{vtx}| < 5$ cm to $|z_{vtx}| < 10$ cm is shown as a function of η bin two p_T bins: 2-4 GeV/c and 4-6 GeV/c. As one can see, the correction factor in fact does depend on the vertex range mainly due to detector acceptance.

The left-hand side of Figure 29 shows the comparison of 1D projected $\Delta\phi$ correlation functions over $0 < |\Delta\eta| < 4.0$ from the 0-5% most central PbPb data for 4 GeV/c $< p_T^{\text{trig}} < 6$ GeV/c, $2 \text{ GeV/c} < p_T^{\text{assoc}} < 4$ GeV/c between $|z_{vtx}| < 15$ cm and $|z_{vtx}| < 5$ cm after corrections are applied. The ratio of $|z_{vtx}| < 15$ cm to $|z_{vtx}| < 5$ cm is shown on the right-hand side of Figure 29. As a result of the discrepancy, a systematic uncertainty of 2.2% is quoted in Table IV.

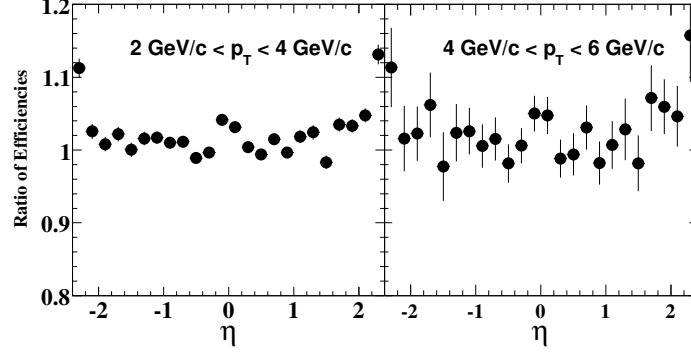


Figure 28. Ratios of tracking efficiency for all tracks for events with z-vertex < 5 cm to events with z-vertex < 10 cm for $2 < p_T < 4$ GeV/c (left), and $4 < p_T < 6$ GeV/c (right).

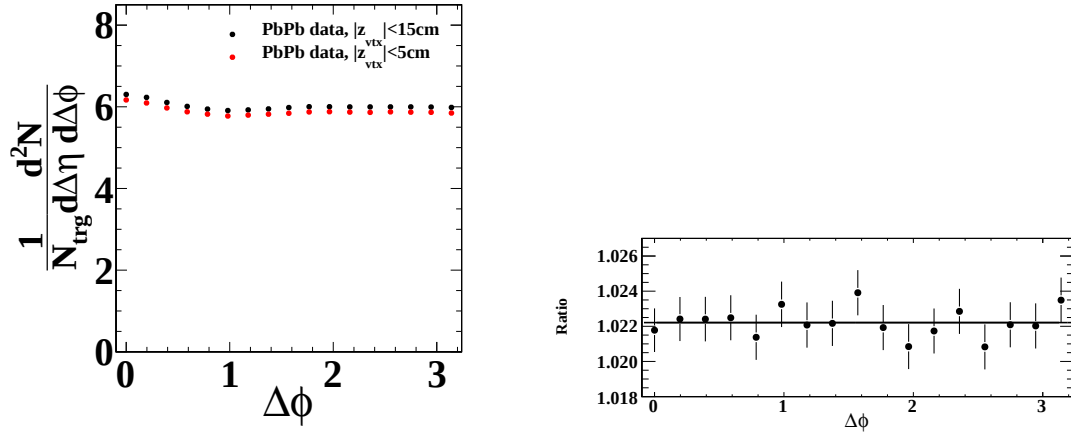


Figure 29. Comparison of 1-D projected $\Delta\phi$ correlation functions over $0 < |\Delta\eta| < 4.0$ from 0-5% most central PbPb data for $4 < p_T^{\text{trig}} < 6$ GeV/c, $2 < p_T^{\text{assoc}} < 4$ GeV/c for two vertex cuts (left), and their ratio (right).

Independent cross check:

In any correlation analysis, there are many subtle decisions with regards to how to perform the analyses that need to be made. Many of these decisions are seemingly arbitrary, but may have real effects on the final results. In absence of a consensus among collaborators as to why one choice is better than another, the best approach that can be taken is to compare the differences in final results, and quote a systematic uncertainty from the comparison.

A cross-check analysis was performed using independent analysis code and some slight differences in technique. One difference was in the way the combinatorial background was handled. In the cross-check analysis, only one background and only one signal histogram were constructed per trigger range set. The vertex bins, of width 2 cm, were still matched between the trigger and associates. However, rather than dividing the signal by the background, vertex bin by vertex bin, the background histograms were summed, then the whole signal was divide by the whole background similarly to methods recently used at RHIC (52).

Another difference in the background is that the primary analysis chooses a random event from which to pull the trigger particles, then chooses a different random event with which to mix them. The cross-check analysis chooses 10 random trigger particles from random events, then mixes them with the associated particles in a different random event. For both the signal and the background, the primary analysis normalizes each

event by the number of triggers event by event, whereas the cross check normalizes the whole histogram by the total number of triggers at the end of the analysis.

This cross check analysis, like the primary, was performed using 15 z-vertex bins between -15 cm and 15 cm, but also with narrower and narrower slices and cuts as far as statistics would allow. In its most restrictive instance, a single bin from -0.1 cm to 0.1 cm, the limit of what statistics would allow, was used, and the results were always found to be consistent with the primary analysis within a few percent.

The results of the cross-check analysis shown in Figure 30 give some idea of the systematic uncertainties in that it is run on the same event sample using the same cuts while producing slightly different results.

When the results are ZYAMed (shifted to have Zero Yield At Minimum), and yields are compared, the agreement of the ridge-region yield is found to be within 2.9%, and that of the jet-region yield within 3.6%. These uncertainties were not included in Table IV. However, they are taken into account in Section 4.1 when yields are calculated.

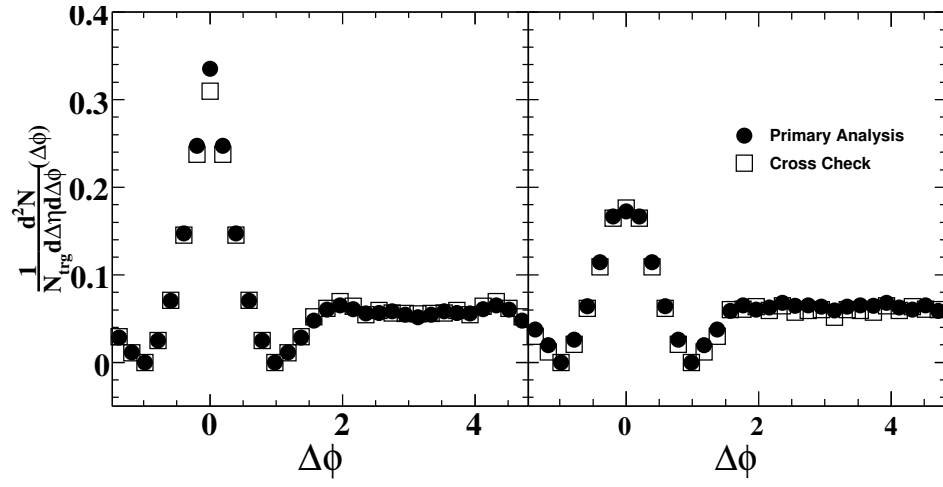


Figure 30. 1-D $\Delta\phi$ per-trigger ZYAMed associated yield of charged hadrons, projected in two $|\Delta\phi|$ intervals, 0-2 (Left) and 2-4 (Right), for primary analysis (closed circles) and cross-check analysis (open squares).

3.9 Technique

The starting point of the analysis is the 2D correlation function which is constructed by first selecting one particle from one p_T interval, called a “trigger” particle (p_T^{trig}), and pairing it with another particle selected from another p_T interval, called an “associated” particle (p_T^{assoc}). The trigger and associated p_T ranges could be the same or different. Traditionally, in the context of jet-like correlations, trigger particles have higher p_T as they are thought to represent the leading particle(s) from a jet, whereas the associated particles surrounding the trigger are thought to have lower p_T .

The construction of the per-trigger associated yield of charged particles, using pairs of charged primary tracks within certain p_T intervals for the trigger and associated particles, is described by the following expression (53):

$$\frac{1}{N_{trig}} \frac{d^2 N^{pair}}{d\Delta\eta d\Delta\phi} = B(0, 0) \times \frac{S(\Delta\eta, \Delta\phi)}{B(\Delta\eta, \Delta\phi)}, \quad (3.1)$$

where $\Delta\eta = (\eta_{assoc} - \eta_{trig})$ and $\Delta\phi = (\phi_{assoc} - \phi_{trig})$ are the relative differences in pseudorapidity and azimuthal angle of the pair. $S(\Delta\eta, \Delta\phi)$ is the measured per-trigger distribution of same-event pairs, $(1/N_{trig})(d^2 N^{same}/d\Delta\eta d\Delta\phi)$ where N_{trig} represents the total number of triggers. N_{trig} includes any particle falling within the selected p_T^{trig} interval, thus it potentially includes multiple triggers from the same event. A mixed-event background distribution is constructed by taking the triggers in each event, and pairing them with

the associates from 10 different random events, being sure to exclude the original event as a pairing possibility. This distribution, $B(\Delta\eta, \Delta\phi)$ ($= (1/N_{trig})(d^2N^{mix}/d\Delta\eta d\Delta\phi)$) is used to account for random combinatorial background and acceptance effects. The constant normalization factor $B(0, 0)$ is calculated as the value of $B(\Delta\eta, \Delta\phi)$ at $\Delta\eta = 0$ and $\Delta\phi = 0$ such that the ratio $B(0, 0)/B(\Delta\eta, \Delta\phi)$ serves as an efficiency and acceptance correction factor used to derive the corrected per-trigger associated yield distribution. Equation 3.1 is calculated in 0.5 cm bins of vertex position along the z-axis (beam direction) and averaged over the range $-15 \text{ cm} < z_{vtx} < 15 \text{ cm}$. Vertex bins of size 2 cm, 0.5 cm, and 0.2 cm have been tested, and all presented results are found to be identical for all three binnings, with the exception of the associated yields presented in Section 4.1, where a systematic error as a result of the differences has been applied.

To optimize the statistics, the quantities $\Delta\eta$ and $\Delta\phi$ are always taken to be absolute values and used to fill one quadrant of the $\Delta\eta, \Delta\phi$ histograms with the other three quadrants filled by reflection. Therefore, the resulting distributions are symmetric about $(\Delta\eta, \Delta\phi) = (0, 0)$ by construction.

When filling the signal and background distributions, each pair is weighted by the product of a correction factor for each of the two particles. The correction factor is the inverse of the efficiency as a function of each particle's pseudorapidity and transverse momentum given by

$$\varepsilon_{trk}(\eta, p_T) = \frac{A(\eta, p_T)E(\eta, p_T)}{1 - F(\eta, p_T)}, \quad (3.2)$$

where $A(\eta, p_T)$ is the geometrical acceptance, $E(\eta, p_T)$ is the reconstruction efficiency, and $F(\eta, p_T)$ is the fraction of misidentified tracks. The details of these functions can be found in Appendix A. The weighting factor changes the overall scale but does not significantly affect the shape of the correlation function.

An example of same-event signal and mixed-event background pair distributions are shown in Figure 31 for $4 < p_T^{\text{trig}} < 6$ GeV/c and $2 < p_T^{\text{assoc}} < 4$ GeV/c in 2.76 TeV 0-5% central PbPb data averaged over all the events. The triangular shape in $\Delta\eta$ is due to the limited acceptance in η such that the phase space for obtaining a pair at very large $\Delta\eta$ drops almost linearly toward the edge of the acceptance. The corresponding raw correlation function, or per-trigger associated yield distribution is shown in Figure 32 as a function of $\Delta\eta$ and $\Delta\phi$.

The two-dimensional (2D) per-trigger-particle associated yield distribution of charged hadrons as a function of $|\Delta\eta|$ and $|\Delta\phi|$ is measured for each of 13 pairings of a p_T^{trig} interval with a p_T^{assoc} interval considered in this analysis, in 12 separate centrality classes. The 13 pairs of p_T bins studied are shown in Table V, and the 12 centrality classes and their corresponding average N_{part} values are shown in Table VI. The N_{part} values are obtained using a Glauber MC simulation.

An example of the resulting 2D correlations for all centralities for trigger particles with $3 < p_T^{\text{trig}} < 3.5$ GeV/c and associated particles with $1 < p_T^{\text{assoc}} < 1.5$ GeV/c is shown in Figure 33, for centralities ranging from the 0-5% most central collisions in the upper

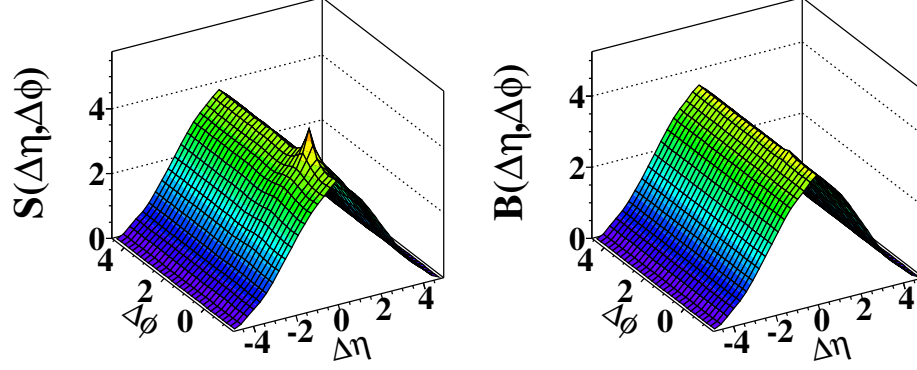


Figure 31. Signal and mixed-event background distributions in 2D for $4 < p_T^{\text{trig}} < 6$ GeV/c and $2 < p_T^{\text{assoc}} < 4$ GeV/c in 2.76 TeV 0-5% central PbPb data.

left-hand corner, to very peripheral events, the 70–80% in the lower right-hand corner.

The 2D correlations for all p_T bins in Table V can be found in Appendix C.

The 2D correlations are rich in structure, and evolve with centrality.

For all centralities there is significant yield centered at $\Delta\phi = \Delta\eta = 0$. This is due to jet fragmentation, and the peak is generally referred to as the near-side jet peak. There is a contribution from the away-side jet, which is centered at $\Delta\phi = 0$, that is harder to see for several reasons. Because the interacting quarks in the initial hard scattering can carry any fraction of the total nucleon momentum, the center of mass of the collision along the z-axis will in general not be the same from collision to collision. Thus the away side jet contribution is spread out in $\Delta\eta$. Due to jet-quenching, or jet-medium

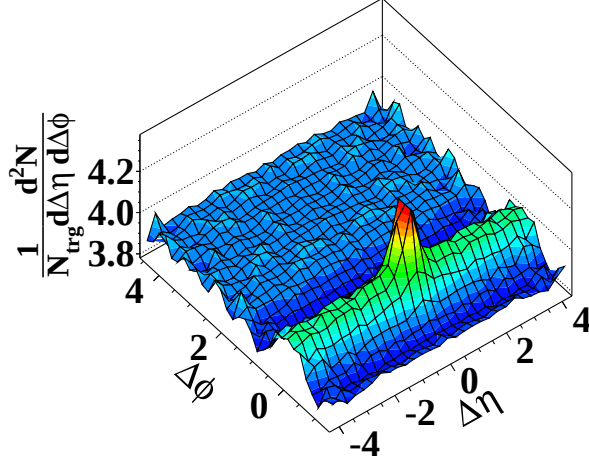


Figure 32. Raw dihadron correlation function in 2D for $4 < p_T^{\text{trig}} < 6$ GeV/c and $2 < p_T^{\text{assoc}} < 4$ GeV/c in 2.76 TeV 0-5% central PbPb data.

interactions discussed in Section 1.4, it is also modified on the away side and even absent from the correlation function for some p_T bins. For the most central PbPb collisions, a clear and significant ridge-like structure is observed at $\Delta\phi \approx 0$, which extends all the way to the limit of $|\Delta\eta| = 4$. Moving to the mid-peripheral events, a pronounced $\cos(2\Delta\phi)$ component emerges, originating from the dominance of the elliptic flow effect (54). Lastly, in the very peripheral collisions, the near-side ridge structure has largely diminished, while the away-side back-to-back jet correlations can be clearly seen at $\Delta\phi \approx \pi$, but spread out in $\Delta\eta$.

TABLE V
THE 13 p_T^{trig} AND p_T^{assoc} BINS CONSIDERED

p_T^{trig}	1.0 – 1.5 GeV/c			
p_T^{assoc}	1.0 – 1.5 GeV/c			
p_T^{trig}	3.0 – 3.5 GeV/c	3.0 – 3.5 GeV/c	3.0 – 3.5 GeV/c	3.0 – 3.5 GeV/c
p_T^{assoc}	1.0 – 1.5 GeV/c	1.5 – 2.0 GeV/c	2.0 – 2.5 GeV/c	2.5 – 3.0 GeV/c
p_T^{trig}	5.0 – 6.0 GeV/c	5.0 – 6.0 GeV/c	5.0 – 6.0 GeV/c	5.0 – 6.0 GeV/c
p_T^{assoc}	1.0 – 1.5 GeV/c	1.5 – 2.0 GeV/c	2.0 – 2.5 GeV/c	2.5 – 3.0 GeV/c
p_T^{trig}	8.0 – 10.0 GeV/c	8.0 – 10.0 GeV/c	8.0 – 10.0 GeV/c	8.0 – 10.0 GeV/c
p_T^{assoc}	1.0 – 1.5 GeV/c	1.5 – 2.0 GeV/c	2.0 – 2.5 GeV/c	2.5 – 3.0 GeV/c

TABLE VI
AVERAGE N_{part} VALUES FOR EACH PbPb CENTRALITY RANGE USED

Centrality	0–5%	5–10%	10–15%	15–20%	20–25%	25–30%
$\langle N_{part} \rangle$	381 ± 2	329 ± 3	283 ± 3	240 ± 3	203 ± 3	171 ± 3
Centrality	30–35%	35–40%	40–50%	50–60%	60–70%	70–80%
$\langle N_{part} \rangle$	142 ± 3	117 ± 3	86.2 ± 2.8	53.5 ± 2.5	30.5 ± 1.8	15.7 ± 1.1

One assumption made in this thesis is that the ridge structure is entirely due to hydrodynamic flow. Although there is a growing consensus that this is in fact the case, as was discussed in Section 1.8, it is worth pointing out that it is an assumption, and the conclusions of this analysis are only valid as far as this assumption is valid. Another assumption made in this thesis is that the flow effects are flat in $\Delta\eta$. Strictly speaking, there is no strong reason to assume this would be the case. Flow signals, as a function of

pseudorapidity has been found to have some curvature (30; 55), however the pairing of triggers from various regions of pseudorapidity with associates from other various regions to form a correlation in $\Delta\eta$, tends to flatten out the structure that is present in η . In early versions of this analysis the effect of the slight bowing of the flow with respect to η was taken into account, and a systematic error was derived. However, the size of this error proved to be several orders of magnitude smaller than the more dominant systematic errors shown in Table IV.

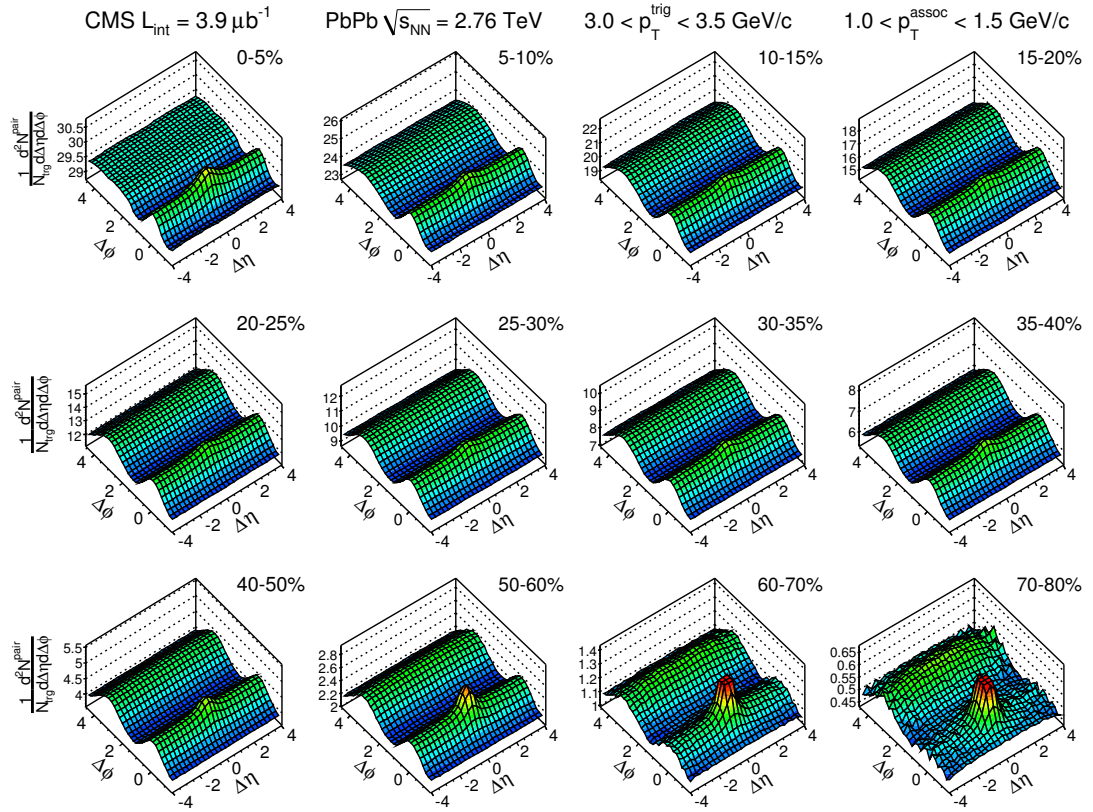


Figure 33. Two-dimensional (2D) per-trigger-particle associated yield of charged hadrons as a function of $|\Delta\eta|$ and $|\Delta\phi|$ for $3 < p_{\text{T}}^{\text{trig}} < 3.5 \text{ GeV/c}$ and $1 < p_{\text{T}}^{\text{assoc}} < 1.5 \text{ GeV/c}$ from twelve centrality ranges of PbPb collisions at $\sqrt{s_{\text{NN}}} = 2.76 \text{ TeV}$. The near-side peak is truncated in the two most peripheral correlations to better display the surrounding structure.

CHAPTER 4

THE RESULTS

4.1 Near Side Flow Subtraction

The first Fourier decomposition analysis of long-range dihadron azimuthal correlations in CMS, for PbPb collisions at $\sqrt{s_{NN}} = 2.76$ TeV was presented in (56). The analysis was motivated by the goal of determining whether the long-range ridge effect could be explained by higher-order hydrodynamic flow harmonics induced by the initial geometry fluctuations. This question is tangential to the purpose of this thesis, however some of the results of the study justify the techniques used here to extract the non-flow yields. Specifically, because the ridge can indeed be explained by hydrodynamic flow alone, the jet contribution to the correlation function (on the near side), can be isolated from the flow contribution by simply subtracting the region where the ridge is clearly visible and isolated (scaled properly as will be defined below) from the region which contains the near-side jet.

As was done in (56), to quantitatively examine the features of short-range and long-range azimuthal correlations, one-dimensional (1D) $\Delta\phi$ correlation functions are calculated by averaging the 2D distributions over a limited region in $\Delta\eta$ from $\Delta\eta_{min}$ to $\Delta\eta_{max}$:

$$\frac{1}{N_{trig}} \frac{dN^{pair}}{d\Delta\phi} = \frac{1}{\Delta\eta_{max} - \Delta\eta_{min}} \int_{\Delta\eta_{min}}^{\Delta\eta_{max}} \frac{1}{N_{trig}} \frac{d^2N^{pair}}{d\Delta\eta d\Delta\phi} d\Delta\eta. \quad (4.1)$$

Specifically, the short-range, or “jet region” $0 < |\Delta\eta| < 1$, and the long-range or “ridge region” $2 < |\Delta\eta| < 4$, are considered. An example of the projected 1D $\Delta\phi$ correlations in the jet region and ridge region for the specific p_T ranges of $3 < p_T^{\text{trig}} < 3.5$ and $1.0 < p_T^{\text{assoc}} < 1.5$ is shown in Figure 34. A version of this plot for each of the p_T bins considered in this analysis (Table V) can be found in Appendix D.

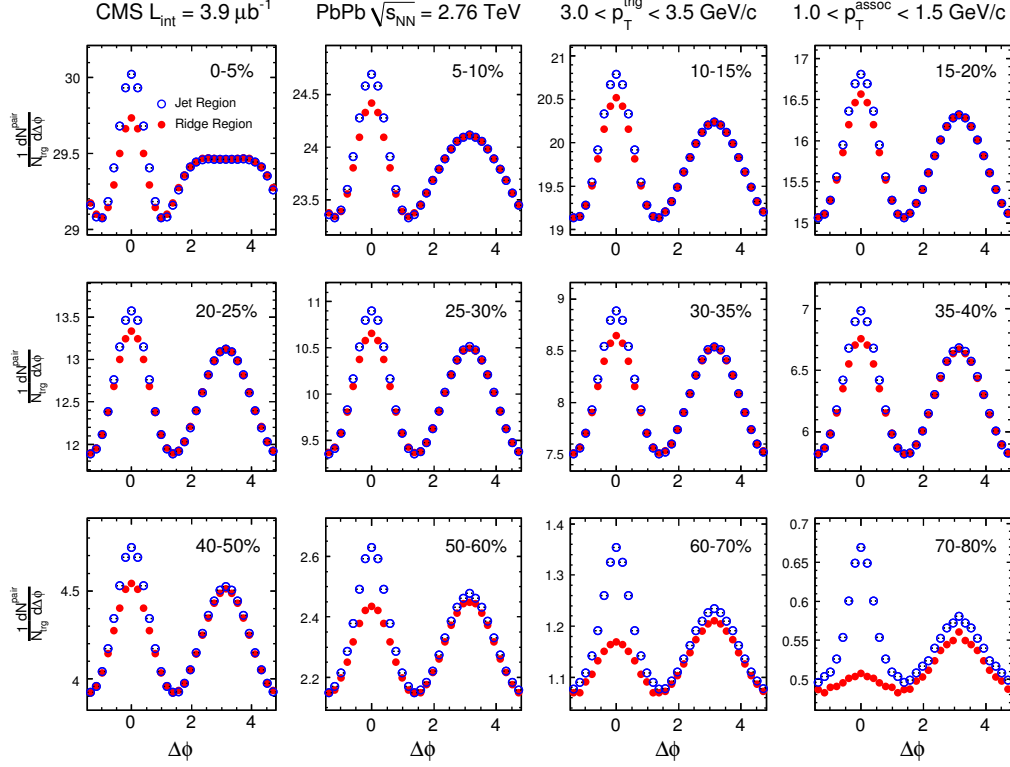


Figure 34. Jet region ($0 < |\Delta\eta| < 1$, blue open circles) and ridge region ($2 < |\Delta\eta| < 4$, red closed circles) per-trigger-particle associated yields of charged hadrons as a function of $|\Delta\phi|$ for $3 < p_{\text{T}}^{\text{trig}} < 3.5$ GeV/c and $1 < p_{\text{T}}^{\text{assoc}} < 1.5$ GeV/c from twelve centrality ranges of PbPb collisions at $\sqrt{s_{\text{NN}}} = 2.76$ TeV. The error bars are statistical only and are too small to be visible in most of the panels. The systematic uncertainties of 7.6% for all data points in the jet region and 7.3% for all data points in the ridge region are not shown in the plots.

The near-side jet contribution is entirely contained within the jet region. It is a good time to remind the reader that it is an assumption of this thesis that ridge observed on the near-side is entirely due to flow, and that the flow contribution is perfectly flat in $\Delta\eta$. The validity of these assumptions was discussed in Section 3.9. It follows that the jet contribution on the near side sits on top of a flow background equal to the yield of the near-side ridge region.

In order to study the near-side jet-region correlation in the absence of the flow, the 1D $\Delta\phi$ distribution in the ridge region is subtracted from that in the short-range region. The resulting difference of the distributions is shown in Figure 35. Appendix E contains the equivalent plots for all p_T bins in Table V. The near-side peak ($\Delta\phi \approx 0$) represents mainly the correlations from jet fragmentation, whereas the away-side region ($\Delta\phi \approx \pi$) is mostly flat and close to zero due to the weak $\Delta\eta$ dependence of the away-side jet peak. The equivalent pp result, also at $\sqrt{s} = 2.76$ TeV, is superimposed in every panel. As expected, the PbPb results tend to converge to the pp result as the collisions become more peripheral. However, the magnitude of the near-side peak is significantly enhanced toward the most central PbPb with respect to pp. The systematic uncertainties in Table IV mostly manifest themselves as an overall change in scale of the correlation functions, with little dependence on $\Delta\phi$ and $\Delta\eta$. Therefore, they are largely canceled when the difference of the short-range and long-range region is taken.

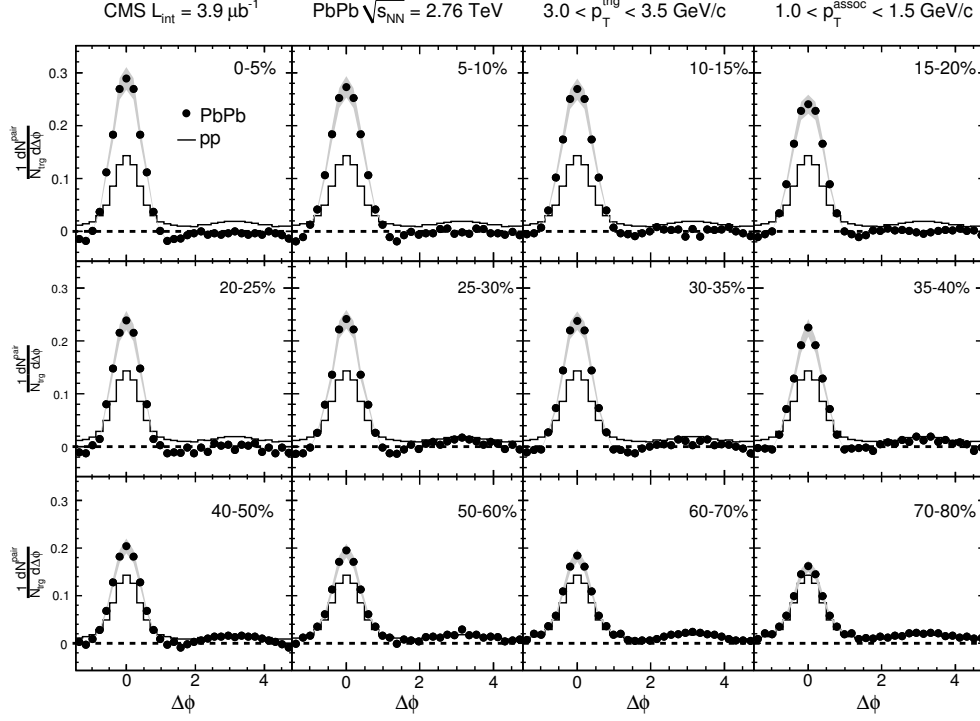


Figure 35. The difference between the jet-region ($0 < |\Delta\eta| < 1$) and ridge-region ($2 < |\Delta\eta| < 4$) per-trigger-particle associated yields of charged hadrons as a function of $|\Delta\phi|$ for $3 < p_T^{\text{trig}} < 3.5$ GeV/c and $1 < p_T^{\text{assoc}} < 1.5$ GeV/c from twelve centrality ranges of PbPb collisions. The statistical error bars are smaller than the marker size, and thus cannot be seen.

The gray bands denote the systematic uncertainties.

The strengths of the near-side peak and away-side region in the $|\Delta\phi|$ distribution from Figure 35 can be quantified by the integral over the $|\Delta\phi|$ ranges separated by the

minimum position of the distribution. This position was chosen to be at $|\Delta\phi| = 1.18$, which was taken as an average of the minima between the near side and away side for all centralities. This choice of integration range introduces an additional systematic uncertainty in the integrated associated yields. The effect of choosing different minima for integration ranges changes the overall yield at most for this example by an absolute shift of 0.007 on the associated yield¹. The shift was calculated for each data point, then added as a percentage in quadrature to the uncertainties in Table IV.

Figure 36 shows the integrated associated yields of the near-side peak and away-side regions as a function of N_{part} , requiring $3 < p_{\text{T}}^{\text{trig}} < 3.5$ GeV/c, for four different intervals of $p_{\text{T}}^{\text{assoc}}$ (1–1.5, 1.5–2, 2–2.5, and 2.5–3 GeV/c). The gray bands again represent the systematic uncertainties. The results from pp collisions at $\sqrt{s} = 2.76$ TeV are again also shown for comparison. The yield of the near-side peak increases by a factor of 1.7 from the very peripheral 70-80% to the most central 0-5% PbPb events, for the lowest $p_{\text{T}}^{\text{assoc}}$ interval of 1–1.5 GeV/c. As $p_{\text{T}}^{\text{assoc}}$ increases, the centrality dependence of the near-side yield tends to become less prominent, and an increase by a factor of only 1.3 is observed. This is of particular interest because at RHIC energies, for $p_{\text{T}}^{\text{assoc}}$ down to 2 GeV/c, and similar $p_{\text{T}}^{\text{trig}}$ ranges and methodology but a lower density system (AuAu $\sqrt{s_{NN}} = 0.2$ TeV), the centrality dependence was found to be approximately flat (57). On both near and

¹Because the flow background has been subtracted off, it would not make sense to quote a percentage for the uncertainty.

away sides, the yield in PbPb matches that in pp for the most peripheral events. On the away side, the yield in PbPb decreases with centrality, going negative for the most central events. This represents a slight concavity in the away-side structure in $\Delta\eta$. This deviation from pp may be related to the jet-quenching phenomena, leading to a modification in the back-to-back jet correlations in PbPb. Any effect that modifies the kinematics of dijet production could also result in a modification of away-side distributions in $\Delta\eta$. More detailed theoretical models will be required to fully understand the origin of this small effect.

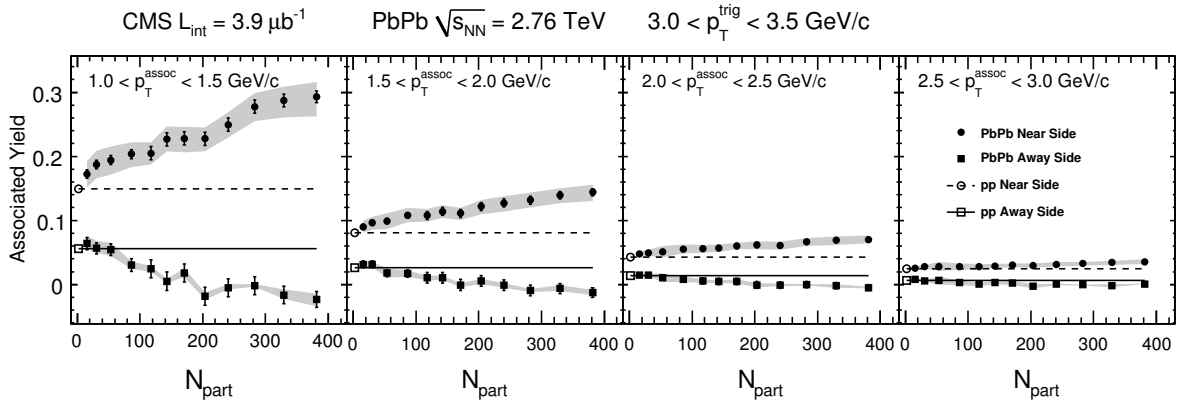


Figure 36. The integrated associated yields of the near-side peak ($|\Delta\phi| < 1.18$) and away-side region ($|\Delta\phi| > 1.18$), requiring $3 < p_T^{\text{trig}} < 3.5$ GeV/c for four different intervals of p_T^{assoc} , as a function of N_{part} in PbPb collisions at $\sqrt{s_{NN}} = 2.76$ TeV. The error bars correspond to statistical uncertainties only, and are too small to be seen for most points, while the gray bands denote the systematic uncertainties. The lines show the results from pp collisions at $\sqrt{s} = 2.76$ TeV.

4.2 Fourier Fitting

The method of subtracting the entire ridge region from the jet region works quite well for the near side; however, on the away side things are more complicated and subtle. Because the away-side jet is spread out in $\Delta\eta$, so much so that there is no qualitative difference between the jet and ridge regions, it is not so simple to determine what part of the structure on the away side is due to flow, and what part is due to non-flow.

The first result from the Fourier decomposition analysis in (56), that is of use to this thesis, was that the ridge can be explained by flow alone. This result was used to justify subtracting the ridge region from the jet region to measure the near side jet yield. A second useful result from the Fourier decomposition analysis is that the correlation function in the ridge region is very well described by the first five terms of a Fourier series. This, in and of itself, is not a profound result¹. Fitting functions well is exactly what Fourier terms are meant to do. The significance here is simply that if one chooses to perform an analysis on the correlation functions Fourier term by Fourier term, then $n \leq 5$ is sufficient.

The 1D $\Delta\phi$ -projected distribution for the ridge region ($2 < |\Delta\eta| < 4$) can be decomposed into a Fourier series given by

¹In fact, this observation is so unprofound, that it often elicits this old physics joke which is remarkably unfunny, yet has survived for decades and, despite poor comedic timing and delivery, consistently gets laughs based on its poignance alone: “With four parameters I can fit an elephant, and with five I can make him wiggle his trunk” - John von Neumann

$$\frac{1}{N_{trig}} \frac{dN^{pair}}{d\Delta\phi} = \frac{N_{assoc}}{2\pi} \left\{ 1 + \sum_{n=1}^{\infty} 2V_{n\Delta} \cos(n\Delta\phi) \right\}, \quad (4.2)$$

where $V_{n\Delta}$ are the Fourier coefficients and N_{assoc} represents the total number of hadron pairs per trigger particle for a given $|\Delta\eta|$ range and $(p_T^{\text{trig}}, p_T^{\text{assoc}})$ bin. Because the Fourier terms form an orthonormal basis, they also represent the best least-squares fit to a function composed of an arbitrary set of terms from that basis. Because it is not inherently obvious that this must be true, it is proven in Appendix B. One consequence of this theorem is that the Fourier coefficients can be obtained by fitting the 1D correlation function with the fit function

$$p_0 [1 + 2p_1 \cos(\Delta\phi) + 2p_2 \cos(2\Delta\phi) + \dots + 2p_n \cos(n\Delta\phi)], \quad (4.3)$$

which is the expansion of Equation 4.2, slightly rewritten, up to arbitrary order n . The p_n are the fit parameters, which for $n > 0$ are equivalent to the $V_{n\Delta}$. An example of the extracted $V_{n\Delta}$ is shown in Figure 37. $V_{n\Delta}$ peaks at $n = 2$ and falls off dramatically for all centralities except the most peripheral (70%–80%).

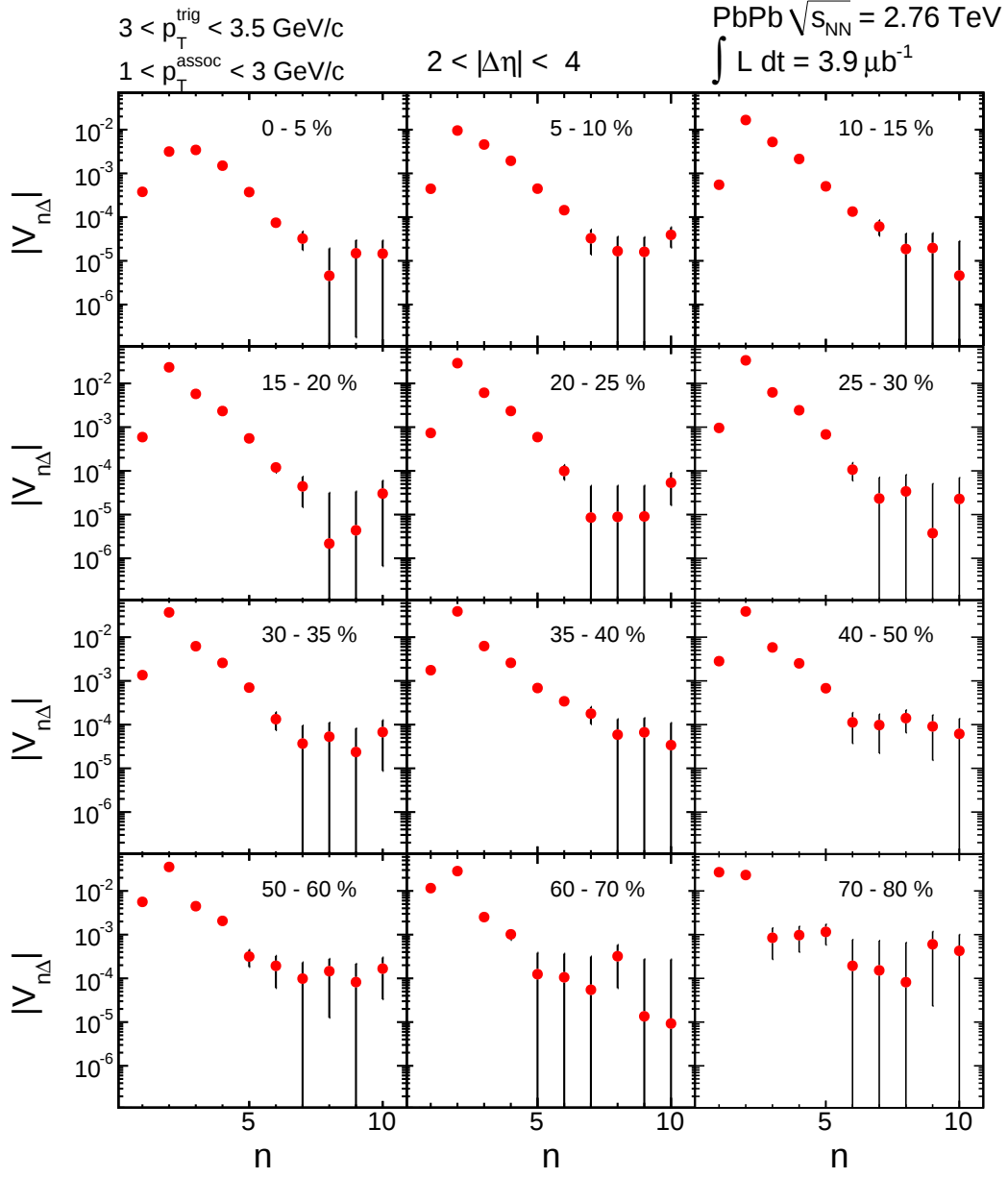


Figure 37. Fourier coefficients, $V_{1\Delta}$ through $V_{10\Delta}$, extracted from the long-range ($2 < |\Delta\eta| < 4$) azimuthal dihadron correlations, for $1 < p_T^{\text{assoc}} < 1.5 \text{ GeV/c}$ and $3 < p_T^{\text{trig}} < 3.5 \text{ GeV/c}$ for all centralities. The error bars correspond to statistical uncertainties.

It is, however, not immediately clear from Figure 37 that $n \leq 5$ is sufficient to describe the correlation function. Figure 38 shows the fit progressively improving as more terms are added to the fit function for central events with $3 < p_T^{\text{trig}} < 3.5 \text{ GeV/c}$ and $1 < p_T^{\text{assoc}} < 1.5 \text{ GeV/c}$ as an example. With each term, the χ^2/dof improves starting at just under 4000 for only the $p_1 - p_2$ fit, but reaching 1.9 by the time the 5th Fourier term is included. This is consistent with the findings in (56), where additional terms are not found to improve the fit significantly.

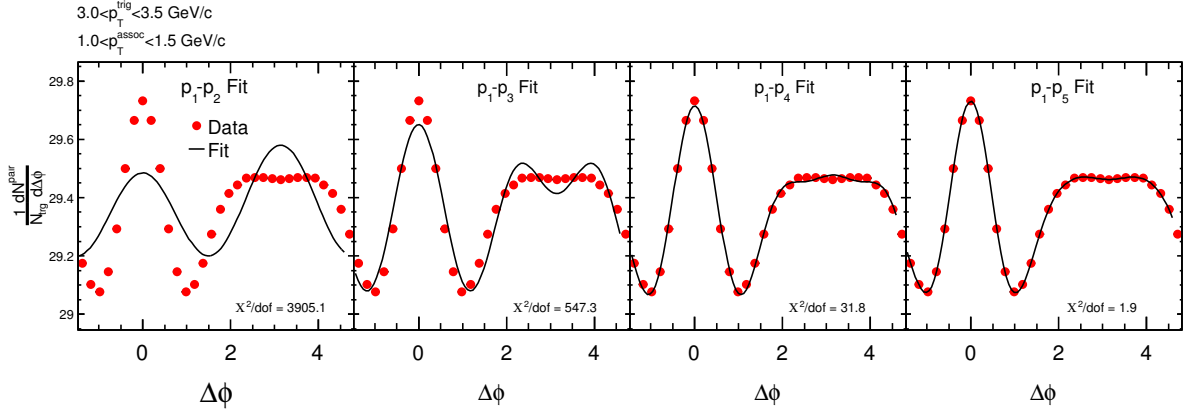


Figure 38. Each panel shows the 1D correlation function for the ridge region, 0 – 5% most central events with $3 < p_T^{\text{trig}} < 3.5 \text{ GeV/c}$ and $1 < p_T^{\text{assoc}} < 1.5 \text{ GeV/c}$ (red circles). The black lines represent the fit function (Equation 4.3), with successive parameters freed from left to right. The right most panel shows the full fit. The χ^2/dof of the fit is shown for each panel.

4.3 Fourier Flow Subtraction

As a first step towards making a flow-subtracted yield measurement on the away side, it is interesting to see what happens when the Fourier terms from Equation 4.2 are subtracted away from the 1D correlation function term by term excluding the $n = 1$ term. Since the $n = 1$ term is not expected to contain any significant information about flow, it will be sensitive primarily to the away-side jet contribution. It therefore makes sense to subtract all other Fourier terms and see what is left on the away side. An illustration of this is shown in Figure 39, where one sees in the leftmost column the original 1D correlations for the jet and ridge regions for 3 different centralities with $3 < p_T^{\text{trig}} < 3.5 \text{ GeV/c}$ and $1 < p_T^{\text{assoc}} < 1.5 \text{ GeV/c}$. Each column to the right subtracts off one more Fourier term starting with the $V_{2\Delta}$ contribution.

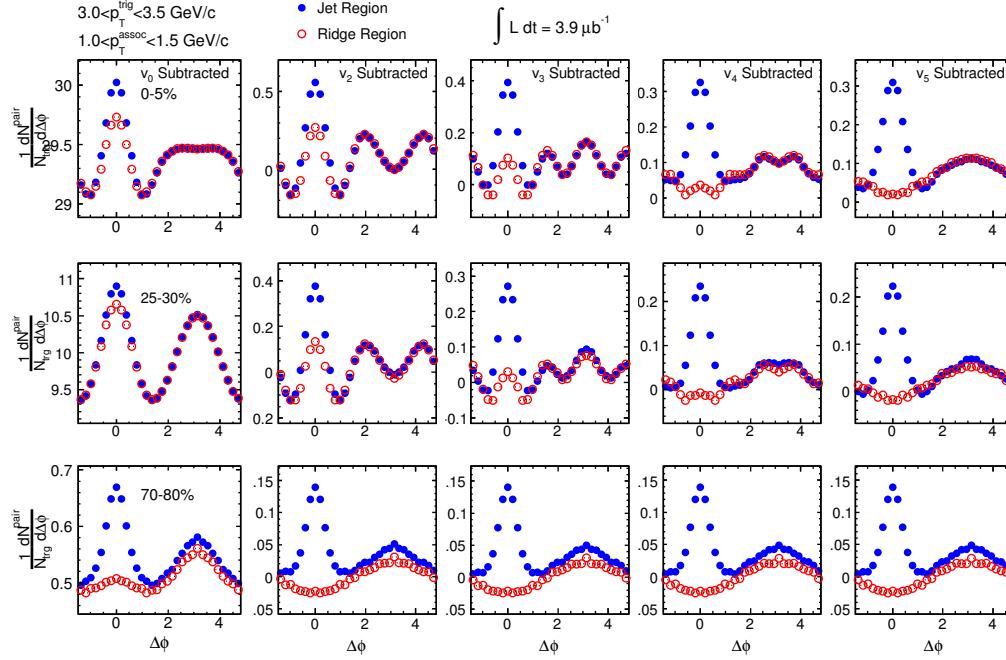


Figure 39. 1D correlation function for $3 < p_T^{\text{trig}} < 3.5 \text{ GeV/c}$ and $1 < p_T^{\text{assoc}} < 1.5 \text{ GeV/c}$, with $V_{n\Delta}$ contribution (not including $V_{1\Delta}$) subtracted from both jet and ridge regions for various orders of n .

It is worth noting that in the second column, where the $V_{2\Delta}$ term has been subtracted, a structure emerges which is similar to many RHIC results, with a “double-hump” on the away side (compare to Figure 9). Although $V_{2\Delta}$ is not precisely the same as the elliptic flow contribution to the correlation function ($\langle v_2(p_T^{\text{trig}}) \rangle \times \langle v_2(p_T^{\text{assoc}}) \rangle$), it is close enough to reveal a similar structure to that which was described in Section 1.7. One now sees

that this once mysterious structure, which spawned many ideas as to its origins, and many complicated analyses to test these ideas, is only one small step in the direction of a truly flow-subtracted result, and that even more exotic artefactual structures emerge at higher orders. After the subtraction of the $n = 5$ term, a smooth structure emerges again.

After the $V_{2\Delta}$ through $V_{5\Delta}$ terms have been removed, there is clearly some yield left over on the away side as can be seen in Figure 40. It would not be correct to say that this is the jet contribution yield, since the $V_{n\Delta}$ are not the flow coefficients, v_n ; i.e. what is subtracted is not exactly the flow, but it is close. One way that it can be immediately seen that this is not a perfect flow subtraction is to look on the near side in the ridge region. If this technique removed the flow exactly, the near side would be flat, and it is not. What is left in the ridge region by this method of flow subtraction looks suspiciously like a cosine wave, which is to be expected given that everything except the $n = 1$ term is subtracted.

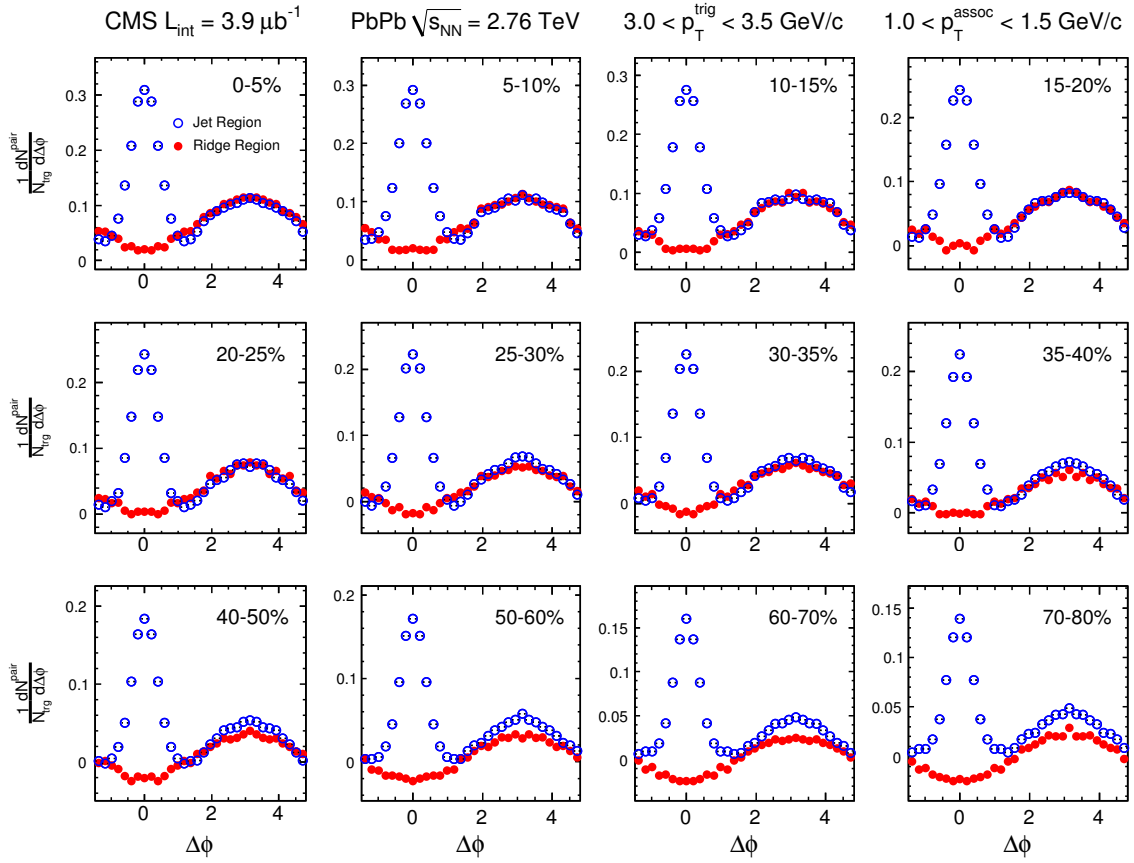


Figure 40. 1D correlation function for $3 < p_{\text{T}}^{\text{trig}} < 3.5 \text{ GeV/c}$ and $1 < p_{\text{T}}^{\text{assoc}} < 1.5 \text{ GeV/c}$, with $V_{2\Delta}$ through $V_{5\Delta}$ contribution subtracted from both jet and ridge regions for all twelve centralities.

4.4 Fourier Plus Gaussian Fitting

In pp collisions and peripheral heavy-ion collisions, the away-side structure is Gaussian in nature (in $\Delta\phi$). One assumes that this away-side structure is created in central heavy-ion collisions as well, however, is modified or quenched as it traverses the medium. If one were to subtract the flow in the ridge region correctly, one might expect to see some sort of Gaussian structure on the away side, and nothing on the near side. To see if the away-side-Gaussian structure can be recovered in more central collisions, the 1D $\Delta\phi$ projection of the ridge region is fit again with the first 5 terms of the Fourier series in Equation 4.2, but this time with an added Gaussian centered at π (the away side). The fit function is modified to now be

$$p_0 \left(1 + p_2 \cos(2\Delta\phi) + 2p_3 \cos(3\Delta\phi) + 2p_4 \cos(4\Delta\phi) + 2p_5 \cos(5\Delta\phi) + p_6 e^{-\frac{1}{2} \left(\frac{x-\pi}{p_7} \right)^2} \right) \quad (4.4)$$

where p_n are again the least-squares-fit parameters. p_2 through p_5 will now be referred to as the “flow-like parameters.” By introducing a Gaussian on the away side, the fit function’s orthogonality is broken, i.e., the terms are no longer independent of each other, and the parameters will depend explicitly on what terms are included in the fitting. This allows parameters 2 through 5 to shift slightly as the Gaussian absorbs the away-side yield. Because the main difference between the Fourier fit parameters $V_{n\Delta}$ and the true flow parameters v_n is the contribution of the away-side jet, and the jet contribution is

absorbed by the away-side Gaussian in the fit, the flow-like parameters should be closer to the true flow parameters.

Parameter p_1 is absent from Equation 4.4 for several reasons. The most important of which is that it is not possible to simultaneously fit the Gaussian and p_1 since they add similar features to the fit function. When p_1 is included in the fit, either it or the Gaussian height parameter p_6 collapse to zero. It turns out that the p_1 term is not needed to get a good fit when the away-side Gaussian is included.

In order to obtain a good fit with a low χ^2/dof , some care has to be taken in the fitting procedure. First, the width of the away-side Gaussian is measured from the peripheral jet region where the away side jet is considered unmodified. The 1D correlation function is fit with Equation 4.4, with parameters p_2 through p_5 fixed to zero, only between $\pi/2$ and $3\pi/2$. In other words, the away side is simply fit with a Gaussian plus a constant. Parameter p_7 is measured from the results of this fit, to be used as a baseline for further fitting (see Figure 41).

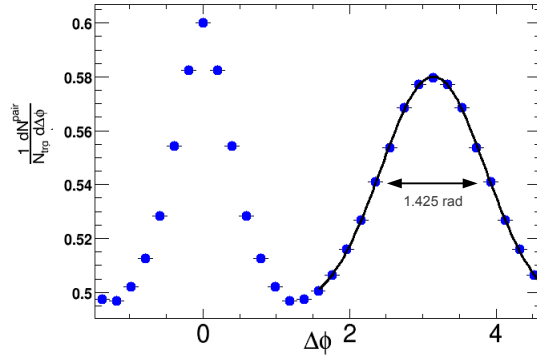


Figure 41. 1D Correlation function for the jet region, 70 – 80% most central events with $3 < p_{\text{T}}^{\text{trig}} < 3.5 \text{ GeV}/c$ and $1 < p_{\text{T}}^{\text{assoc}} < 1.5 \text{ GeV}/c$. The closed blue circles are the data points, and the line is the the fit of a Gaussian plus a constant centered at π .

Next, the 1D correlation function of interest is fit between $\pi/2$ and $3\pi/2$ with Equation 4.4 with parameters p_2 through p_5 fixed to zero, and parameter p_7 (the Gaussian width), fixed to what was found in the peripheral jet region. An example is shown in Figure 42. The purpose of this fit is to gain a reasonable starting point for parameter p_6 , the height of the Gaussian.

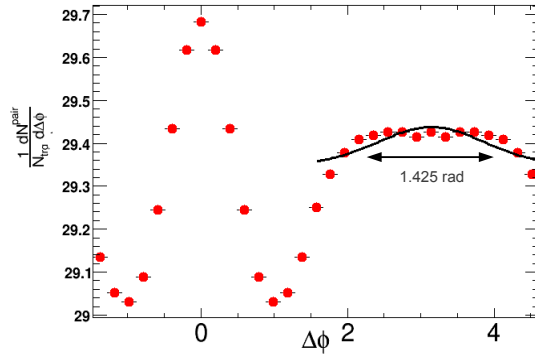


Figure 42. 1D correlation function for the ridge region, 0 – 5% most central events with $3 < p_T^{\text{trig}} < 3.5 \text{ GeV/c}$ and $1 < p_T^{\text{assoc}} < 1.5 \text{ GeV/c}$. The closed red circles are the data points, and the line is the the fit of a Gaussian centered at π with fixed width 1.425 rad.

Finally the fitting of the full $\Delta\phi$ range is performed in a series of iterations where each flow term (p_2 through p_5) is added successively, each time using the results of the previous fit as a starting value. The width of the Gaussian, p_7 , is never allowed to vary.

In principle, it is expected that the shape of the away side jet will be modified as it traverses the medium; however, in order to gain a consistent meaning for the extracted yield with respect to centrality, the width is fixed. Figure 43 shows an example of the successive fitting and the associated χ^2/dof . As can be seen in the right-most panel, a good fit is achieved in this example without the inclusion of the $n = 1$ term $V_{1\Delta}$ ¹.

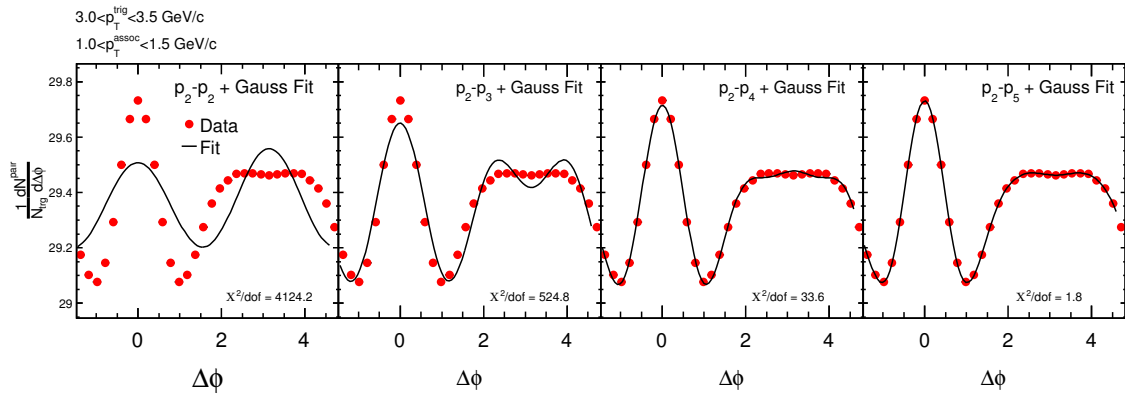


Figure 43. Each panel shows the 1D correlation function for the ridge region, 0 – 5% most central events with $3 < p_T^{\text{trig}} < 3.5$ GeV/c and $1 < p_T^{\text{assoc}} < 1.5$ GeV/c (red circles). The black lines represent the fit function (Equation 4.4), with successive parameters freed from left to right. The rightmost panel shows the full fit.

¹The χ^2/dof is actually slightly lower than it was in Figure 38, where the $n = 1$ term was included and there was no away-side Gaussian, indicating an even better fit.

The χ^2/dof for all centralities as a function of fit order n are shown in Figure 44. A good fit is achieved using this method for every centrality in this example. It is perhaps also worth noting that the χ^2/dof appears to converge to its minimum value at smaller orders in the most peripheral bins compared to the most central. This is likely because initial state fluctuations are expected to play a smaller role in peripheral collisions, (see Section 1.8), and thus higher order Fourier harmonics are less necessary to describe the shape.

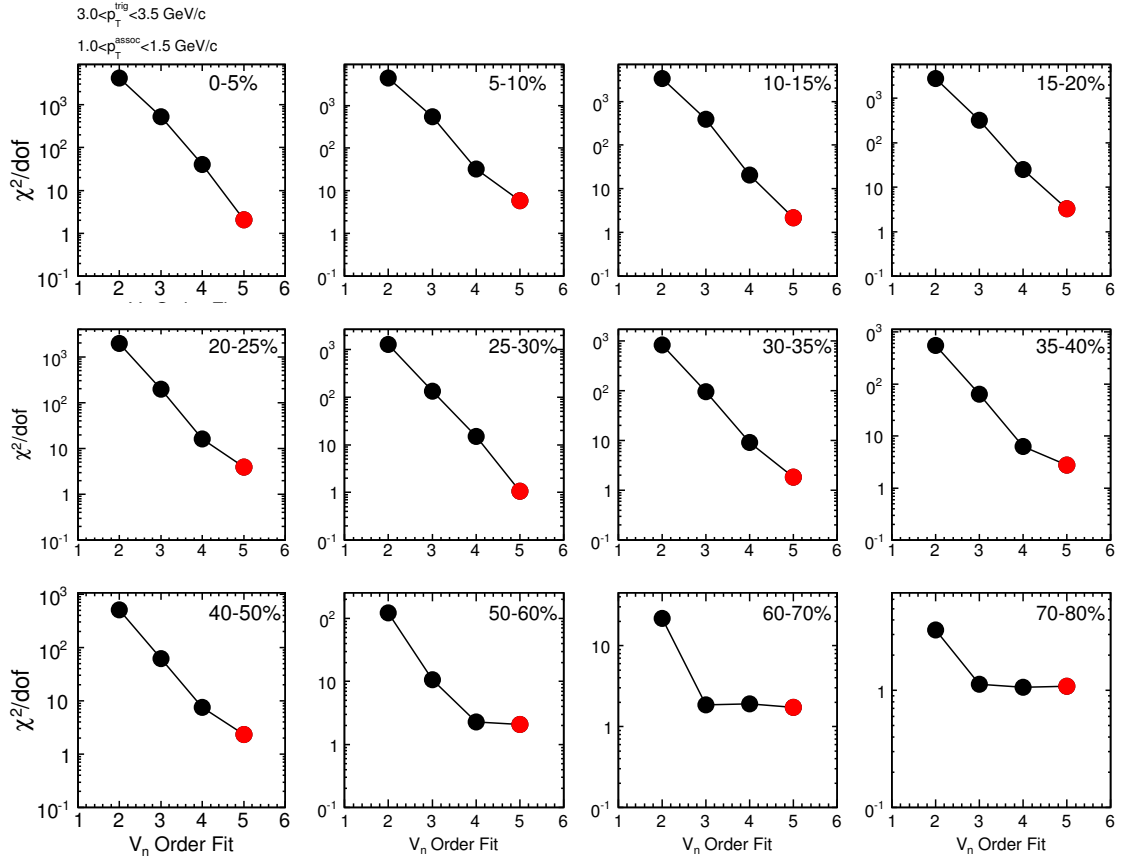


Figure 44. Chi square per degree of freedom for 12 centralities as a function of fit order for $3 < p_T^{\text{trig}} < 3.5 \text{ GeV/c}$ and $1 < p_T^{\text{assoc}} < 1.5 \text{ GeV/c}$. The red circles represent the final fit.

A slightly better fit is achieved for peripheral events than for central ones, as can be seen in Figure 45, where the χ^2/dof is plotted as a function of N_{part} . This is not surprising as the away-side jet contribution is expected to be Gaussian in peripheral events, but may be less so in central events.

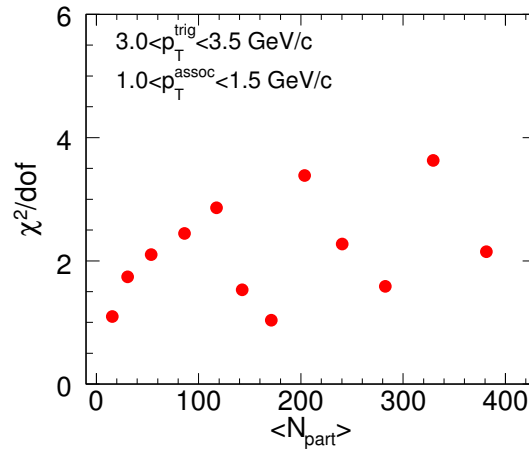


Figure 45. Chi square per degree of freedom of the final fit as a function N_{part} for $3 < p_T^{trig} < 3.5$ GeV/c and $1 < p_T^{assoc} < 1.5$ GeV/c.

Figure 46 shows fit parameters p_2 through p_5 as a function of N_{part} at each step of the fitting procedure. Several of this plot's features are of interest. First, the fact that the parameters seem to vary in a smooth and controlled fashion is a first indication that

the method is at least under control. Because the Gaussian is absorbing yield on the away side only, there is a decrease on the away side of the yield available for the flow-like parameters. This means that even flow-like parameters can be expected to decrease and odd flow-like parameters to increase with the introduction of the away-side Gaussian. This is exactly what can be seen in Figure 46.

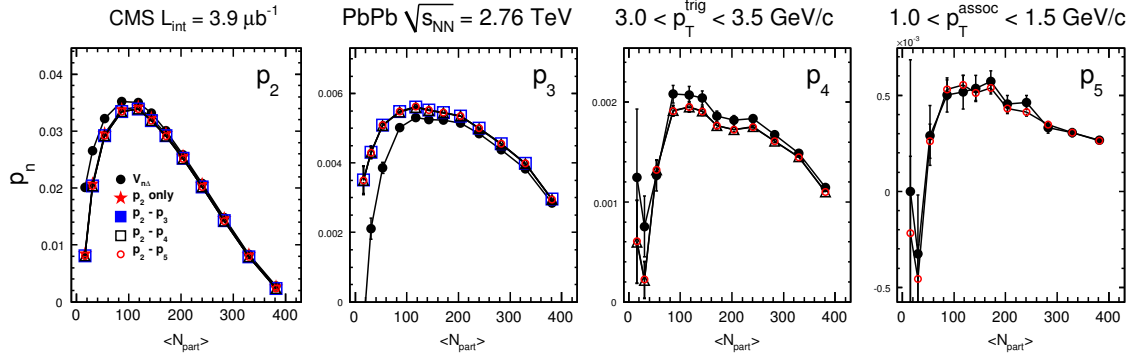


Figure 46. Original fit parameter $V_{n\Delta}$ and flow-like parameters p_2 through p_5 for various steps in the fitting procedure. The different markers represent different steps in the fitting procedure. The fact that the p_2 -only fit through $p_2 - p_5$ fit parameters are all on top of each other indicates that the fitting procedure is stable.

4.5 Fourier Plus Gaussian Flow Subtraction

A more precise method of flow subtraction than that given in Section 4.3 is to subtract the fit function (Equation 4.4), using the flow-like parameters obtained by the fitting procedure described in Section 4.4, however, with parameter p_6 explicitly set to zero, thus leaving the away-side Gaussian. Figure 47 shows what is left after subtracting off the flow-like terms from Equation 4.4 progressively term by term. This is the equivalent of Figure 39 in Section 4.3 where the Fourier terms $V_{n\Delta}$ were subtracted off progressively, except here it is the flow-like terms. It is perhaps worth repeating that the difference between the two figures is that the Fourier terms in Figure 39 are obtained by fitting without the added away-side Gaussian which was used here to obtain Figure 47, and thus are influenced more by the away-side jet contribution. The two plots are quite similar, except for one remarkable feature. In Figure 47, in the right most column, on the near side, in the ridge region (red open circles), the correlation function is now nearly flat.

This means that the ridge has been exactly subtracted away by only the $n=2$ through $n=5$ flow related Fourier terms. If it is true that the ridge phenomenon is entirely due to flow, this strongly suggests that the flow contribution to the correlation function has been completely subtracted on the away side as well. Thus what remains on the away side is the true away side-jet yield, at least to the extent that the near-side ridge region is flat.

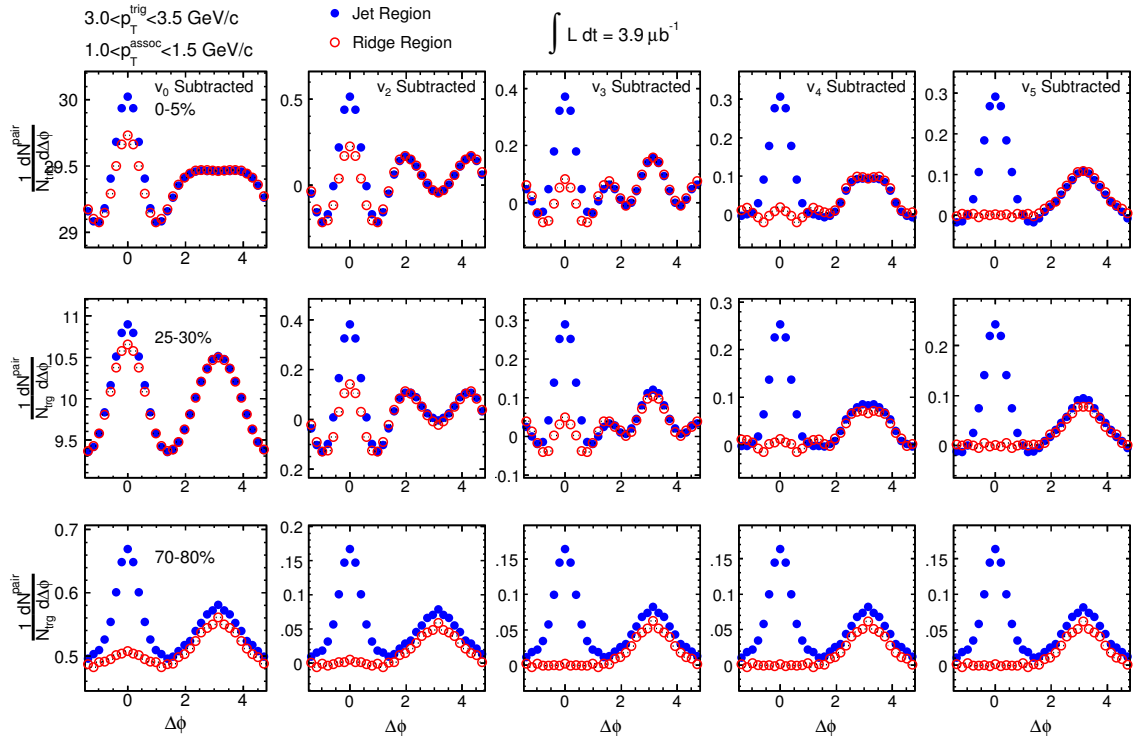


Figure 47. 1D correlation function for $3 < p_T^{\text{trig}} < 3.5 \text{ GeV/c}$ and $1 < p_T^{\text{assoc}} < 1.5 \text{ GeV/c}$, with p_n contribution subtracted from both jet and ridge regions for various orders of n .

Figure 48 shows an example of the flow-subtracted result for all centrality bins. In all cases, there is significant yield left on the away side compared to the relatively flat near-side ridge region.

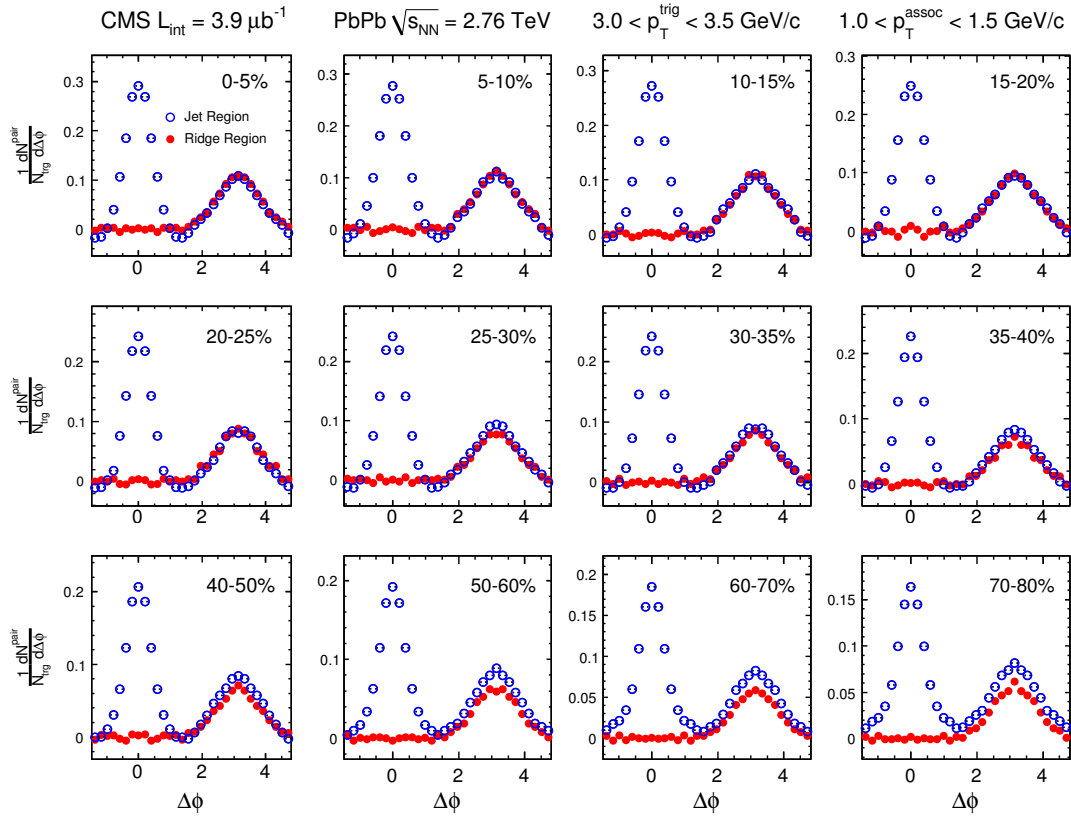


Figure 48. Ridge region and jet region after subtraction of flow-like terms for $3 < p_T^{\text{trig}} < 3.5$ and $1 < p_T^{\text{assoc}} < 1.5$.

This method does not work for all p_T bins considered in the analysis (Table V), or at least it does not produce results with an immediate and obvious interpretation. The equivalent of Figure 48 for all p_T bins can be found in Appendix G. It is interesting to see that for relatively low p_T^{assoc} , the technique works well for all p_T^{trig} regions. However, as the p_T^{assoc} starts to climb, something interesting happens. The residual away-side yield first becomes flat for central collisions, then negative for central collisions, all the while remaining positive for peripheral collisions. In all of these cases a good fit is achieved, and the near-side ridge region ends up relatively flat after subtraction, meaning that the results can be trusted at least as far as making the measurement is concerned. Whether or not it is meaningful to say there is negative yield in central events on the away side after flow has been subtracted is open to interpretation. This strange behavior does, however, seem to be a physics result, rather than an artifact of the technique, and it will require more theoretical input before it can be interpreted.

Once Figure 48 is obtained, the away-side jet yield independent of the contribution from hydrodynamic flow can for the first time be measured. The final away-side yields of the ridge region for all 4 p_T^{trig} bins, each with the lowest p_T^{assoc} bin of $1 < p_T^{\text{assoc}} < 1.5 \text{ GeV}/c$, are shown in Figure 49. At this low p_T^{assoc} , there is a dramatic increase in yield from peripheral to central for all 4 examples. Ridge-region yields ($2 < |\Delta\eta| < 4$) are shown here in the text, and jet-region yields ($0 < |\Delta\eta| < 1$) can be found in Appendix H. The jet-region yields show similar features, however because the integration range of the

jet region is half that of the ridge region, the results are less clear due to statistical fluctuations, larger error bars and uncertainties.

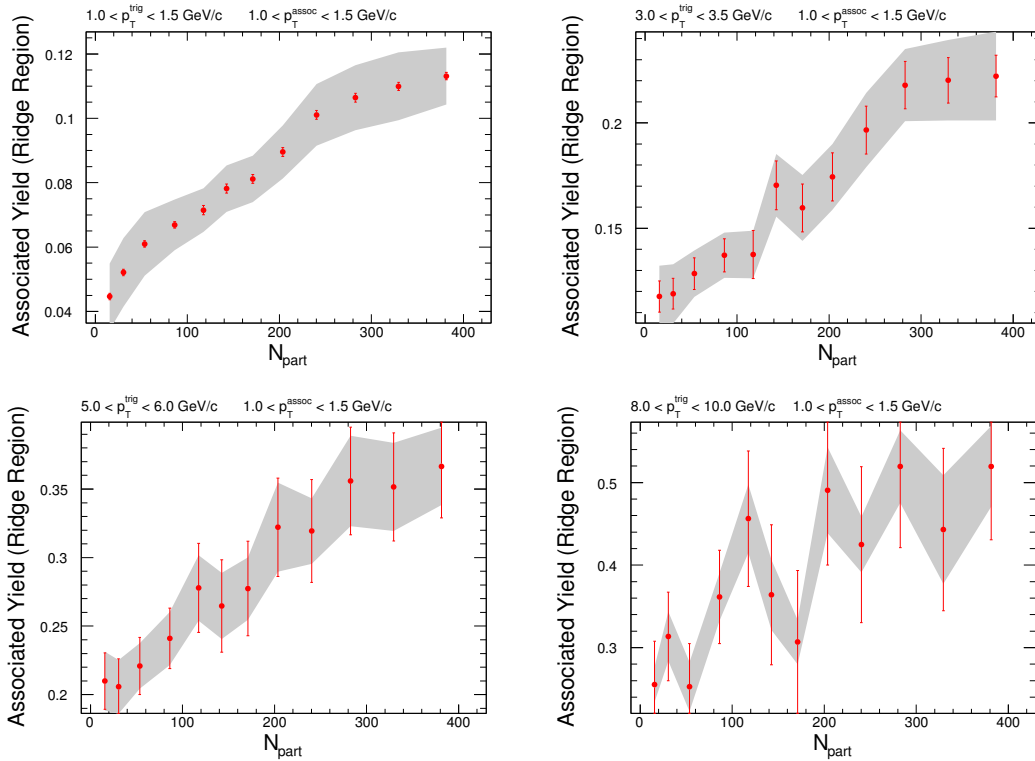


Figure 49. Away-side flow-subtracted ridge-region yields ($2 < |\Delta\eta| < 4$) for $1 < p_{\text{T}}^{\text{trig}} < 1.5$ GeV/c (top left), $3 < p_{\text{T}}^{\text{trig}} < 3.5$ GeV/c (top right), $5 < p_{\text{T}}^{\text{trig}} < 6$ GeV/c (bottom left), and $8 < p_{\text{T}}^{\text{trig}} < 10$ GeV/c (bottom right), all with $1 < p_{\text{T}}^{\text{assoc}} < 1.5$ GeV/c. A systematic error consisting of the RMS of the residuals on the near side of the ridge region (see Figure 48) is added in quadrature to the systematic errors already incorporated into the yields, in order to take any non-complete flatness into consideration.

Figure 50, Figure 51, and Figure 52 show all four p_T^{assoc} ranges for low, mid, and high p_T^{trig} respectively. The clear trend shown in these figures is that for the lowest p_T^{assoc} bin for all p_T^{trig} bins, the yield increases with centrality. In other words, there are more low- p_T particles in central events than in peripheral events. However, for only slightly higher p_T the trend is reversed. This is a surprising and previously unseen result which should be of interest to heavy-ion theorists.

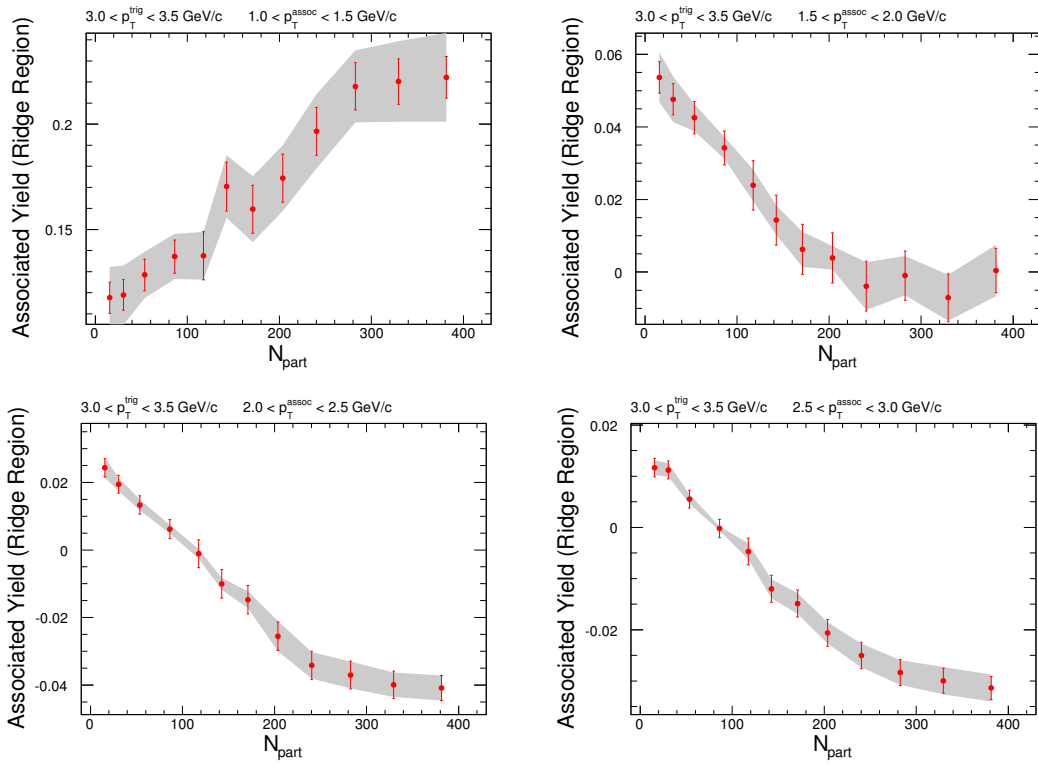


Figure 50. Away-side flow-subtracted ridge-region yields ($2 < |\Delta\eta| < 4$) for $3 < p_T^{\text{trig}} < 3.5 \text{ GeV/c}$ and $1 < p_T^{\text{assoc}} < 1.5 \text{ GeV/c}$ (upper left), $1.5 < p_T^{\text{assoc}} < 2 \text{ GeV/c}$ (upper right), $2 < p_T^{\text{assoc}} < 2.5 \text{ GeV/c}$ (lower left), $2.5 < p_T^{\text{assoc}} < 3.5 \text{ GeV/c}$ (lower right).

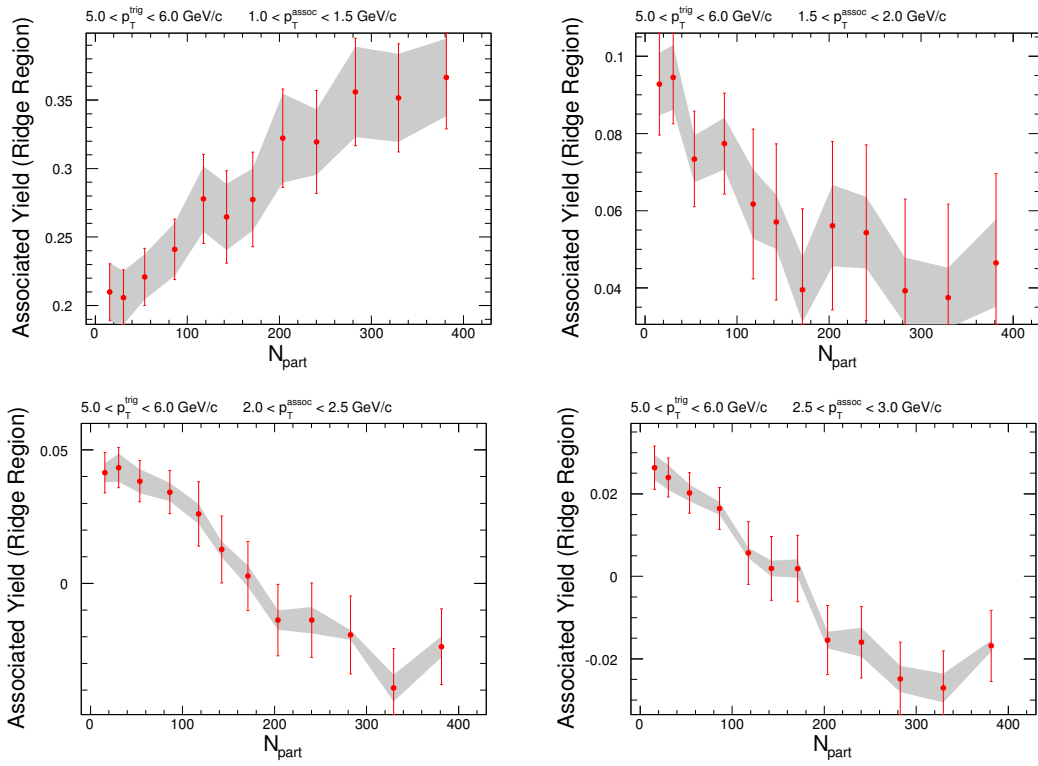


Figure 51. Away-side flow-subtracted ridge-region yields ($2 < |\Delta\eta| < 4$) for $5 < p_T^{\text{trig}} < 6 \text{ GeV/c}$ and $1 < p_T^{\text{assoc}} < 1.5 \text{ GeV/c}$ (upper left), $1.5 < p_T^{\text{assoc}} < 2 \text{ GeV/c}$ (upper right), $2 < p_T^{\text{assoc}} < 2.5 \text{ GeV/c}$ (lower left), $2.5 < p_T^{\text{assoc}} < 3.5 \text{ GeV/c}$ (lower right).

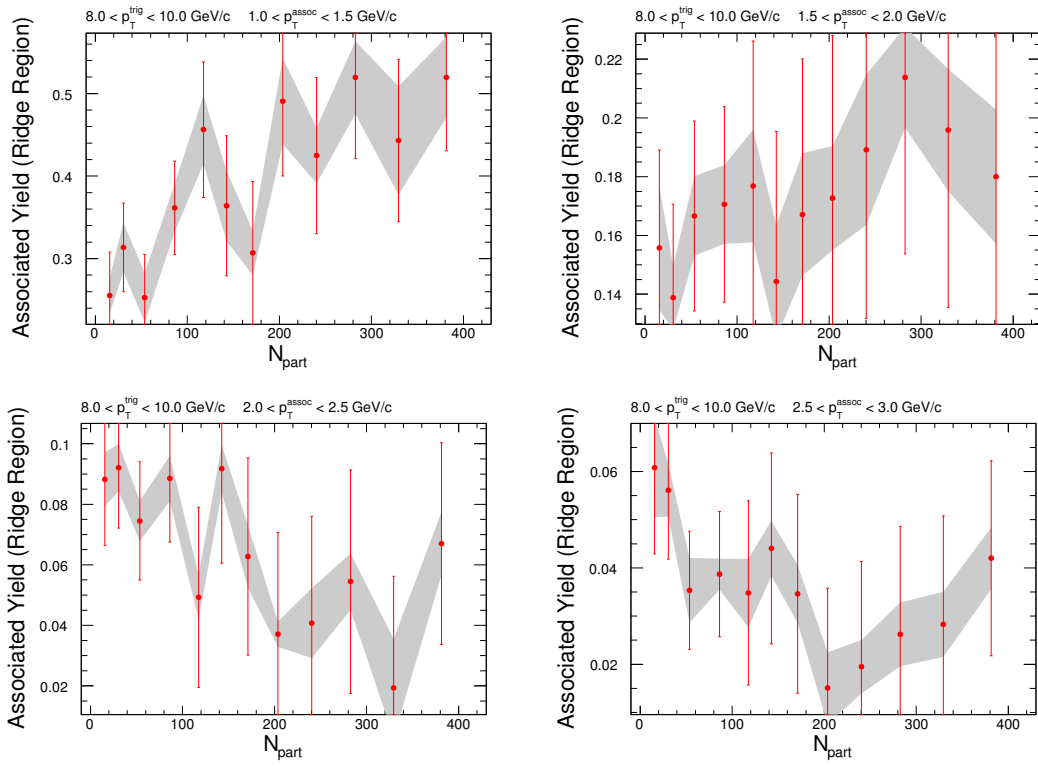


Figure 52. Away-side flow-subtracted ridge-region yields for $8 < p_T^{\text{trig}} < 10 \text{ GeV/c}$ and $1 < p_T^{\text{assoc}} < 1.5 \text{ GeV/c}$ (upper left), $1.5 < p_T^{\text{assoc}} < 2 \text{ GeV/c}$ (upper right), $2 < p_T^{\text{assoc}} < 2.5 \text{ GeV/c}$ (lower left), $2.5 < p_T^{\text{assoc}} < 3.0 \text{ GeV/c}$ (lower right).

CHAPTER 5

SUMMARY AND OUTLOOK

5.1 Summary

The near-side and away-side jet yields from two-particle dihadron correlations in PbPb collisions at $\sqrt{s_{NN}} = 2.76$ TeV have been measured using the CMS detector at the LHC. The results have been presented over the full relative azimuthal angle $\Delta\phi$, over a very wide relative pseudorapidity range $|\Delta\eta| < 4$, over an order of magnitude in trigger transverse momentum ($1 < p_T < 10$ GeV/c), and from low to mid associate transverse momentum ($1 < p_T^{\text{assoc}} < 3$ GeV/c). The 2D correlation function can be characterized by the following features:

- The near-side jet peak is the spike around $(\Delta\eta, \Delta\phi) \approx (0,0)$. It is present for all centralities and p_T bins.
- The near-side ridge is the ridge extending the full range of $\Delta\eta$ along $\Delta\phi = 0$. It is visible in central and mid-central collisions for all p_T ranges considered in this analysis.
- On the away side, the correlation function has a shape in $\Delta\phi$ that depends greatly on the centrality and the p_T bins, but is generally uniform in $\Delta\eta$. Within this feature of the 2D correlation function is both a contribution from hydrodynamic flow and the away-side jet, which is spread out in $\Delta\eta$.

The near-side jet peaks have been isolated from the ridge by subtracting off the ridge contribution. This is a simple new technique that is a direct consequence of the realization that the ridge may be primarily due to flow and may not contain any jet information. A novel new method of isolating the jet signal from the flow on the away side has also been presented. This method involves fitting the correlation function with the first five terms from a Fourier series plus a Gaussian centered at $\Delta\phi = \pi$, then subtracting only the Fourier terms away. The jet yields on both the near side and on the away side have been measured. The near-side jet yield increases with centrality which is a result not seen in earlier experiments. On the away side, the jet yield increases with centrality for low p_T^{assoc} , but then the trend reverses at moderate p_T^{assoc} .

5.2 Outlook

In the early days of dihadron correlation studies at RHIC, the exotic structures such as the ridge and the double hump described in Section 1.7 were surprising and not well understood. Theorists dreamed up some rather complicated ideas to explain their origins (23; 24; 25; 26; 27; 58; 59; 60). It is now clear that one possibility is the simple explanation that they are both due to hydrodynamic flow that manifests itself relatively uniformly in pseudorapidity η , but can have exotic shapes in azimuthal angle ϕ due to the “lumpiness” of the initial state. Results consistent with this explanation continue to

be produced and a consensus is growing. The Occam's razor argument is becoming more difficult to ignore¹.

This momentary detour into the space of askew and perhaps misguided ideas should not be seen as an error on the part of scientists, but rather a necessary part of the research process, and even a testament to human creativity. The ability to imagine scenarios that can explain the evidence at hand is at the core of scientific discovery, for without this, the results of an experiment would have no value. They would simply be either baffling, or as expected, and progress would go no further. It is actually creativity that moves science forward. An unfortunate but necessary byproduct of scientific ingenuity is the proliferation of erroneous hypotheses. More generally, bad ideas are a side effect of creativity.

Ultimately accepting the flow explanation for the exotic structures in dihadron correlations will allow physicists to get back to the task of characterizing some of the simpler physics of the QGP. Having a firm handle on what happens to the yields of jets on both the near side and the away side as a function of centrality and transverse momentum is an important step in having a clear understanding of the energy-loss mechanism in the medium. The results presented in this thesis are thus an important piece of the QGP puzzle.

¹Occam's razor is the rule which dictates one should accept among hypotheses the one which makes the fewest assumptions and therefore offers the simplest explanation.

The 2011 heavy-ion run at the LHC provided an order of magnitude more collisions to work with than the 2010 data which was used in this thesis. This leads to much smaller statistical errors, and the ability to reach much higher in p_T . It should be interesting to see if perhaps the techniques introduced here can be refined with the smoother correlation functions from larger sets of data. There are also currently other analyses underway in CMS and other experiments that may provide a more accurate picture of the jet structures. At the 2012 Hard Probes conference in June, and later this year at the 2012 Quark Matter conference in August, correlation results will be seen where, rather than using dihadrons, identified calorimeter jets will be correlated with tracker tracks. In other words, the jet axis will be known from jet-finding algorithms in the calorimeters, and will be correlated against charged particles in the Tracker.

Another interesting category of analyses that is currently underway, is the study of dijet asymmetry. Events are selected that show an asymmetry between back-to-back calorimeter jets, and the distribution of calorimeter energy is studied. It would be quite interesting to perform dihadron correlation studies on these events, where a medium effect on the away side is more or less guaranteed. Perhaps the technique introduced in this thesis to separate the away-side jet signal from the flow will be of use to these studies as well, and provide theorists with new information to ponder.

APPENDICES

Appendix A

FULL TRACK PERFORMANCE

The tracking acceptance, efficiency and fake rate of the full tracking collection as derived from the most central 0-5% HYDJET MC are shown in Figure 53 as a function of p_T and η . The 1D projections are shown in Figure 54.

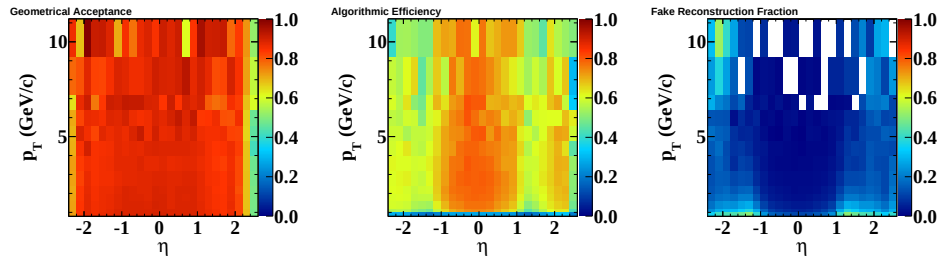


Figure 53. Tracking acceptance, efficiency and fake rate of the full tracking collection after selections are plotted as a function of η and p_T in 2D derived from the most central 0-5% HYDJET MC.

Appendix A (Continued)

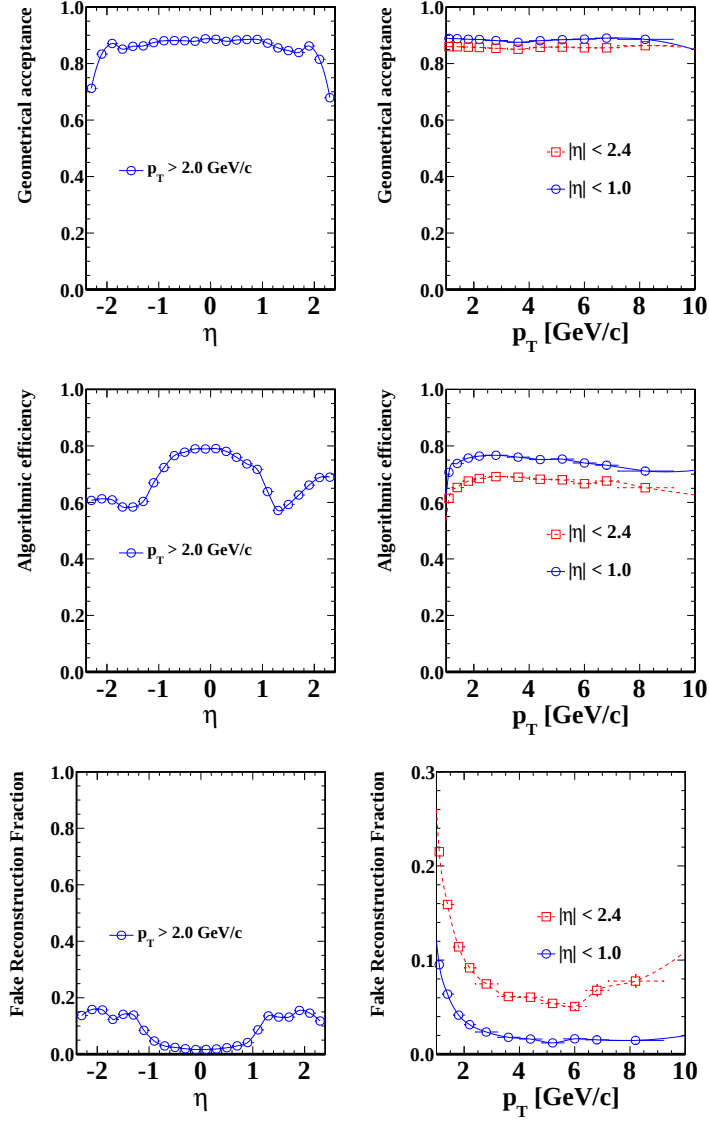


Figure 54. Tracking acceptance (top), efficiency (middle) and fake rate (bottom) of the full tracking collection after selections, as a function of η (left) and p_T (right).

Appendix A (Continued)

Simulation studies show that the combined geometrical acceptance and reconstruction efficiency for the global primary track reconstruction reaches about 60% for the 0-5% most central PbPb collisions at $p_T > 2 \text{ GeV}/c$ over the full CMS tracker acceptance ($|\eta| < 2.4$) and 65% at $|\eta| < 1.0$ for charged hadrons. The percentage of fake tracks is 1-2% at $|\eta| < 1.0$ but goes up to 10% at $\eta \approx 2.4$.

Dead channels in the pixel detector cause an asymmetry of the tracking efficiency with respect to positive and negative η above $|\eta| = 1.5$. Figure 55 shows a snapshot of online DQM plots for run 151923 for the pixel tracker, where the dead channels can clearly be seen. The different panels show the occupancy of different layers of the pixel detector including the barrel and endcap regions. The white spaces are dead channels. In endcap +z disk 2, there is even a wedge that is completely missing. This missing wedge was discovered after the generation of the MC samples used for calculating the tracking efficiency, and was thus not properly simulated. All the other dead channels were properly simulated in the global tag used for the MC events. To account for the missing wedge, the region was simply masked out when calculating the efficiency in MC. The large number of channels missing in endcap -z disk 2, results in slightly lower tracking efficiency on the negative η side in Figure 54 (middle left). Similarly, the η distributions for reconstructed tracks on the left hand side of Figure 57, also show a slight asymmetry with more tracks on the positive η side.

Appendix A (Continued)

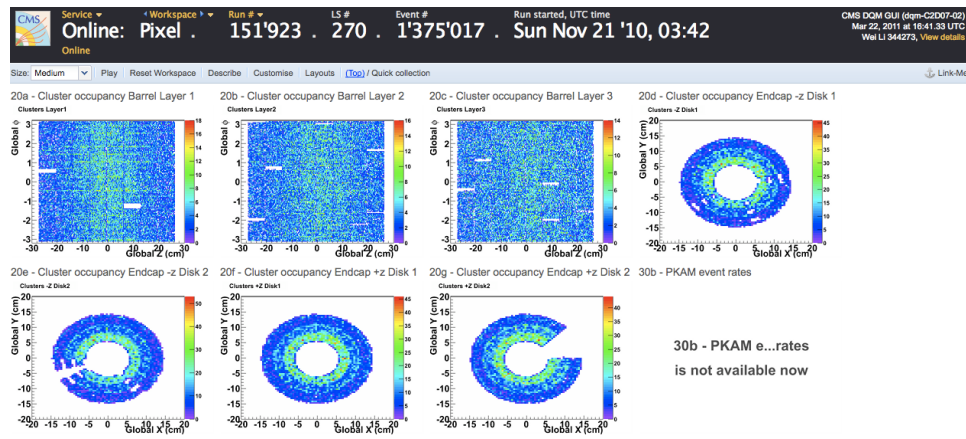


Figure 55. Screenshot of DQM plots for run 151923 for pixel hits occupancy in various layers of the pixel detector including barrel and endcap regions.

Appendix A (Continued)

Figure 56, Figure 57, and Figure 58 show the distributions of tracking variables where the data is compared to two Monte Carlo generators, HYDJET and AMPT. These figures show the transverse momentum spectrum, pseudorapidity distribution, azimuthal distribution, goodness of fit, number of valid hits, and longitudinal distance of closest approach between the track and the reconstructed vertex. The dip on the azimuthal distribution for both data and MC is caused by the non-uniform geometry of the tracker.

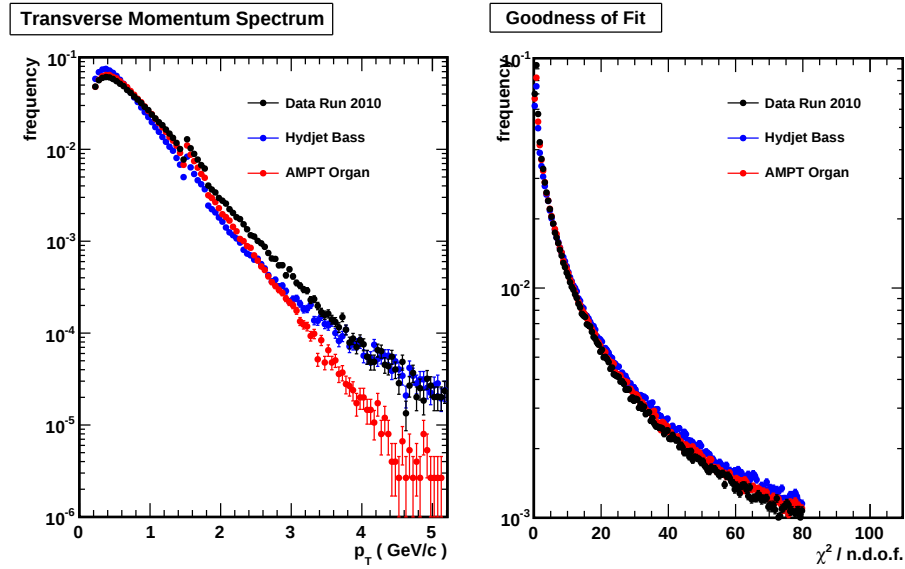


Figure 56. Comparison of the p_T spectrum and χ^2 distribution between reconstructed merged tracks in data, HYDJET simulation, and AMPT simulation

Appendix A (Continued)

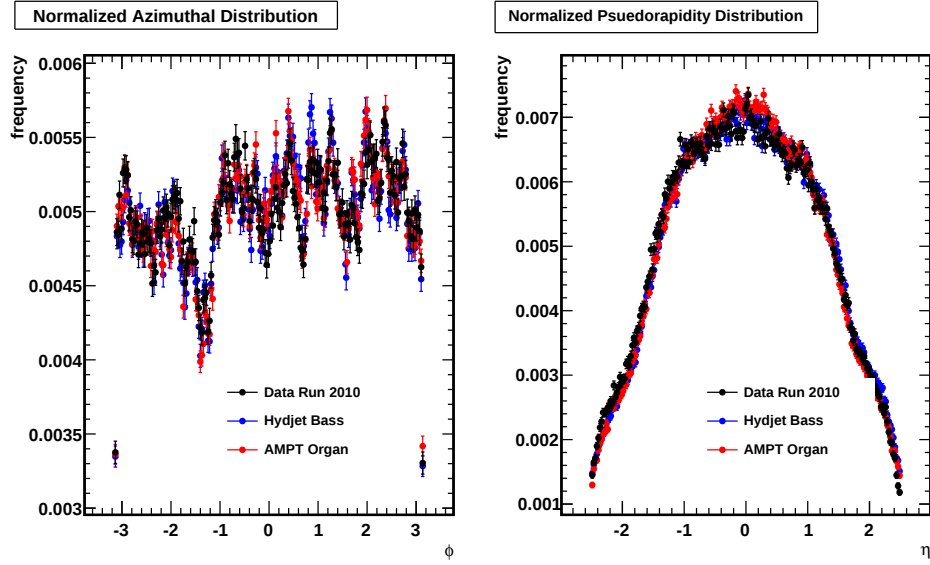


Figure 57. Comparison of the pseudorapidity and azimuthal distribution between reconstructed merged tracks in data, HYDJET simulation, and AMPT simulation

In principle, the background occupancy of the pixel and strip detectors may be different in simulation and in actual heavy-ion collisions. A simulation may also fail to reproduce the effects of the electronics and noise faithfully. It is thus important to also consider a data driven understanding of the track reconstruction efficiency.

The DataMixer tool was used to embed a set of 20 simulated pions into actual minimum-bias heavy-ion events. The vertex of the simulated pions was matched to the reconstructed vertex of the heavy-ion event at the time of generation. The pions

Appendix A (Continued)

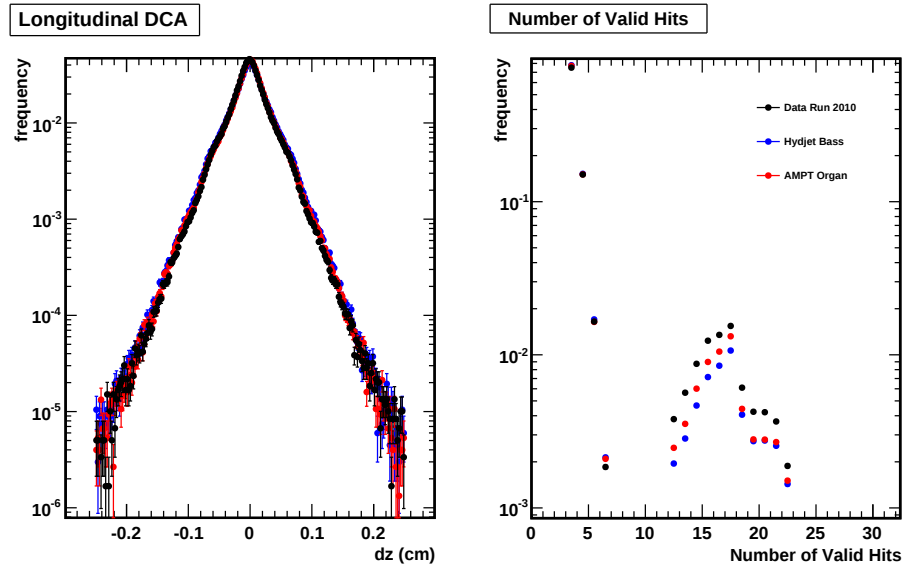


Figure 58. Comparison of the distribution of the number of valid hits and the longitudinal distance of closest approach between reconstructed merged tracks in data, HYDJET simulation, and AMPT simulation

Appendix A (Continued)

were generated to have a flat p_T spectrum of 0.2 to 5.0 GeV/c and pseudorapidity range of $|\eta| < 2.4$.

One limitation of this technique is that there is a difference between the heavy-ion event and the embedded pions in terms of the alignment of the pixel and strip detectors. This could cause a mismatch between the hits corresponding to the real particles and theoretically it could affect the probability of a simulated track being reconstructed. Another limitation is that the misalignment may prevent the reconstruction of the vertex after the pions have been embedded. Instead, the reconstructed vertex is replaced by a “dummy” vertex which is set to the origin of the generated pions and given a fixed error.

Results comparing the embedded pions and minimum bias HYDJET simulation are shown in Figure 59 and Figure 60. The results agree well between the full simulation and embedding, excepting the low p_T range of the high pseudorapidity tracks. This discrepancy is likely due to the large fixed error on the dummy vertex, which effectively loosens the cut on the pixel tracks.

Appendix A (Continued)

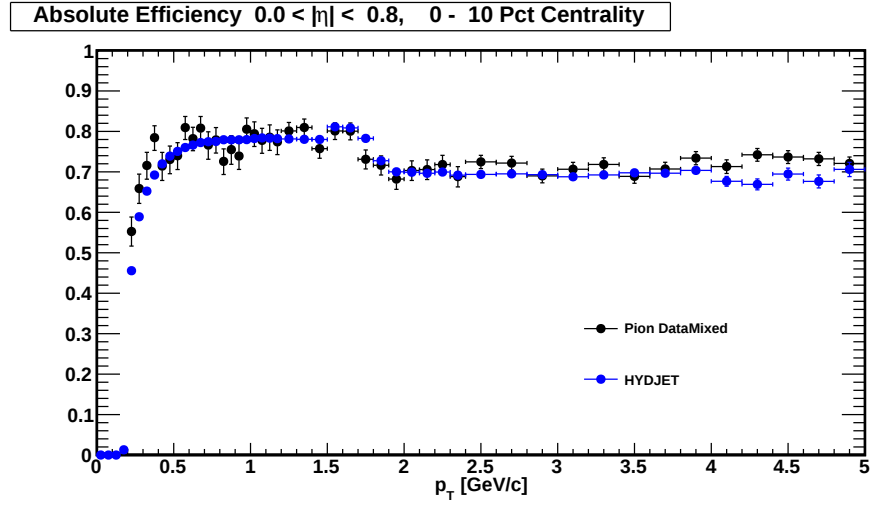


Figure 59. Absolute efficiency of particles simulated with HYDJET compared to pions embedded into heavy-ion minimum-bias events. Results from the 10% most central event are plotted.

Appendix A (Continued)

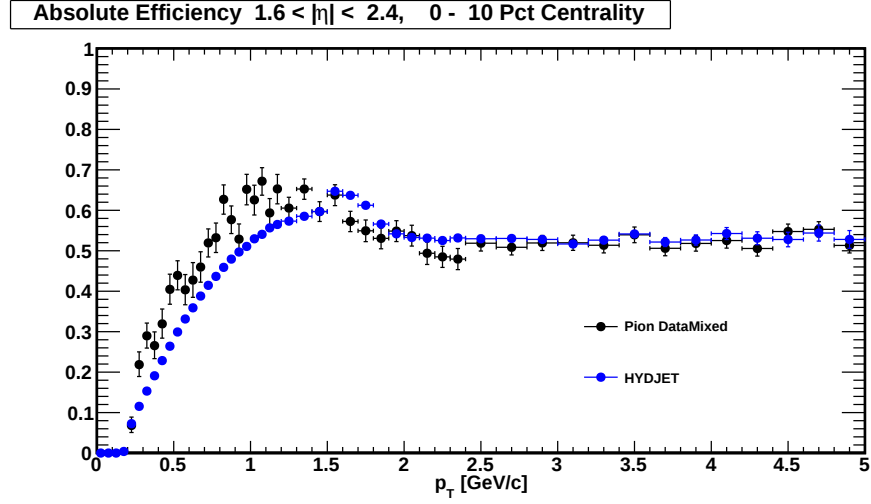


Figure 60. Absolute efficiency of particles simulated with HYDJET compared to pions embedded into heavy ion minimum bias events. Results from the 10% most central event are plotted.

Appendix A (Continued)

The following plots show the tracking variables for the AllPhysics Rereco data set, the Core Physics Promptreco set, and the HYDJET Bass simulation. These plots are here just for reference, and generally show good agreement between the data sets.

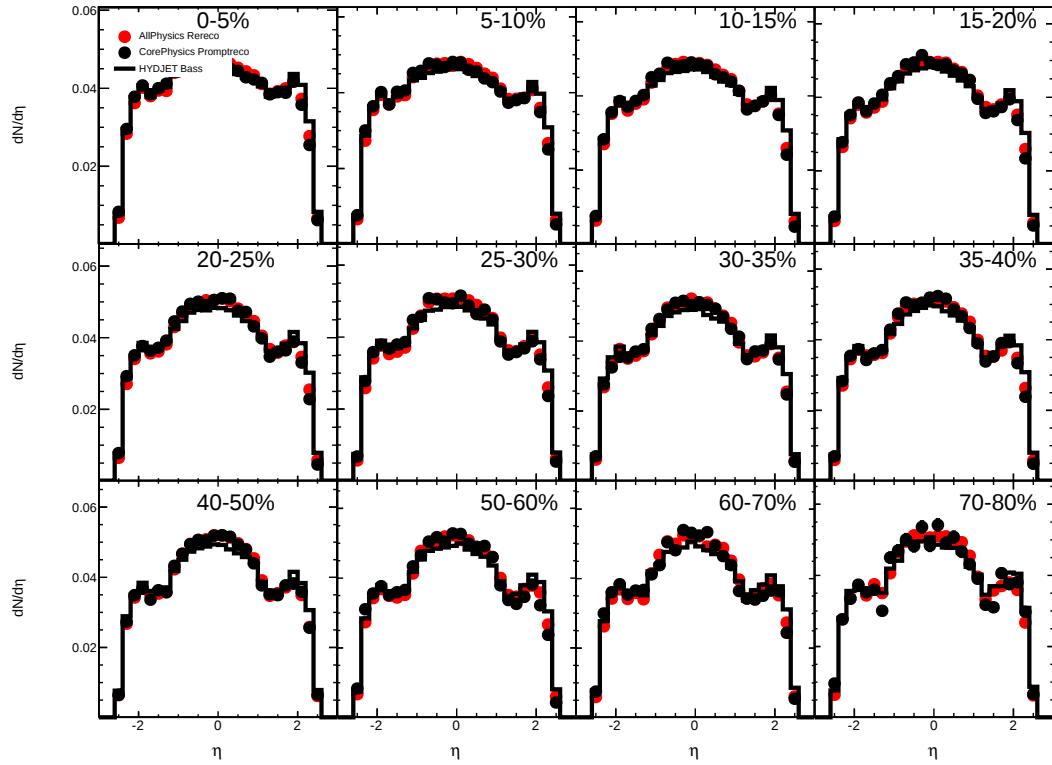
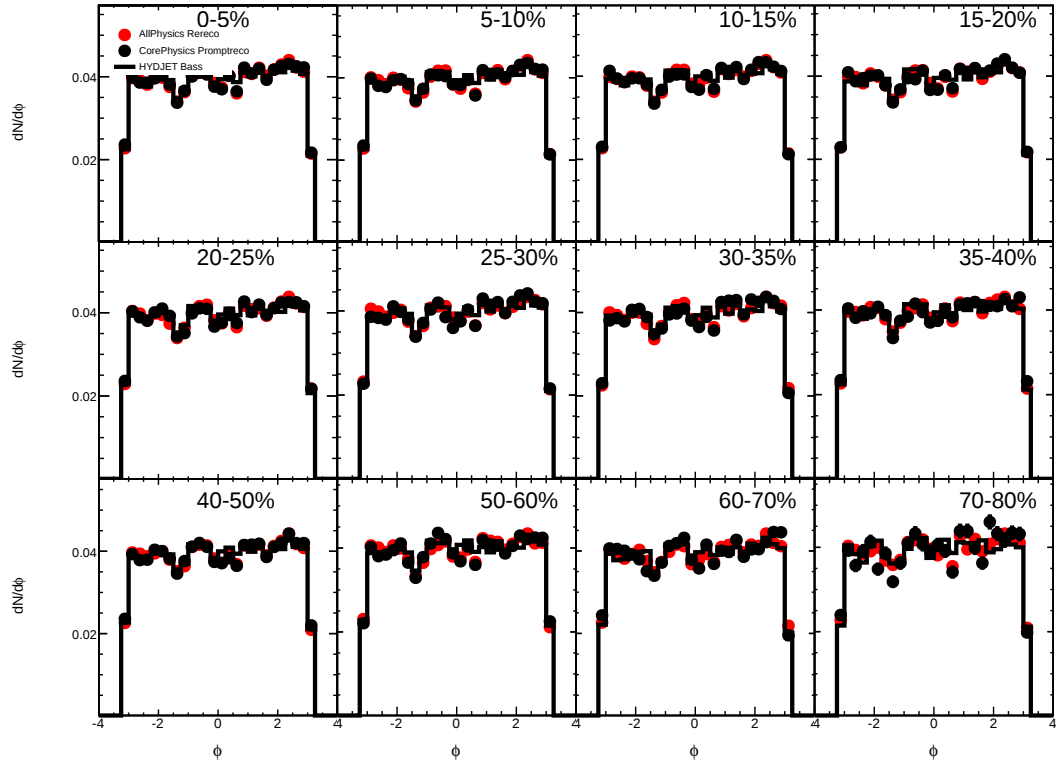


Figure 61. η distributions in 12 bins of centralities for CorePhysics prompt reconstruction data set, AllPhysics re-reconstruction data set and HYDJET PbPb MC simulations for tracks above 1 GeV/c.

Appendix A (Continued)

Figure 62. ϕ distributions for the three data sets.

Appendix A (Continued)

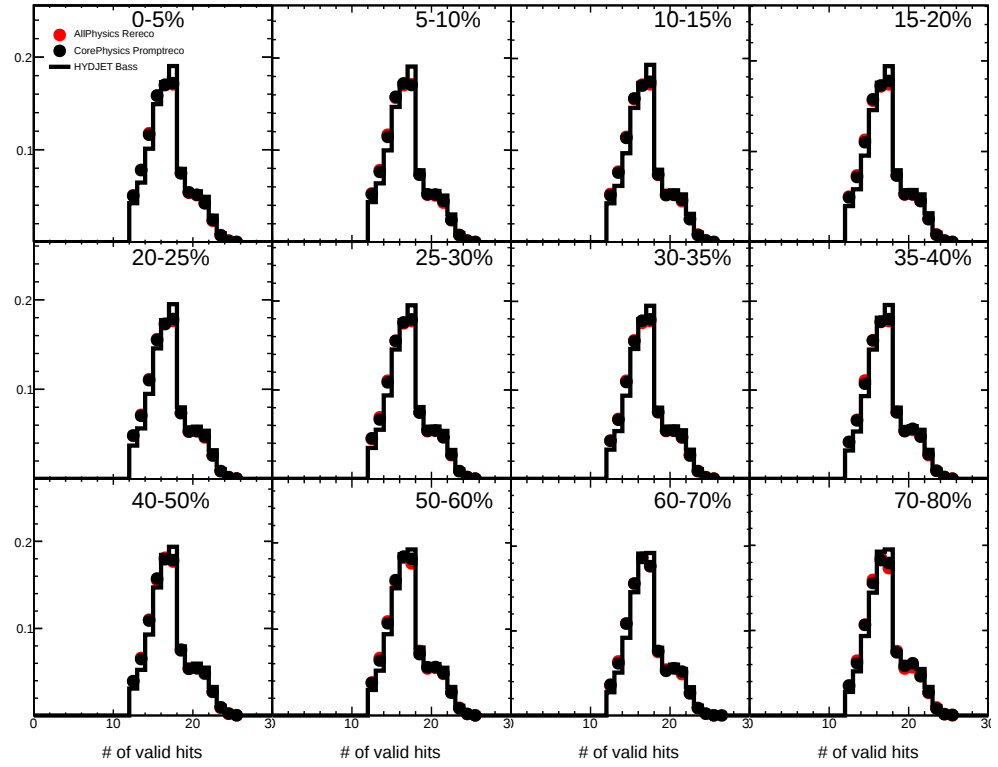
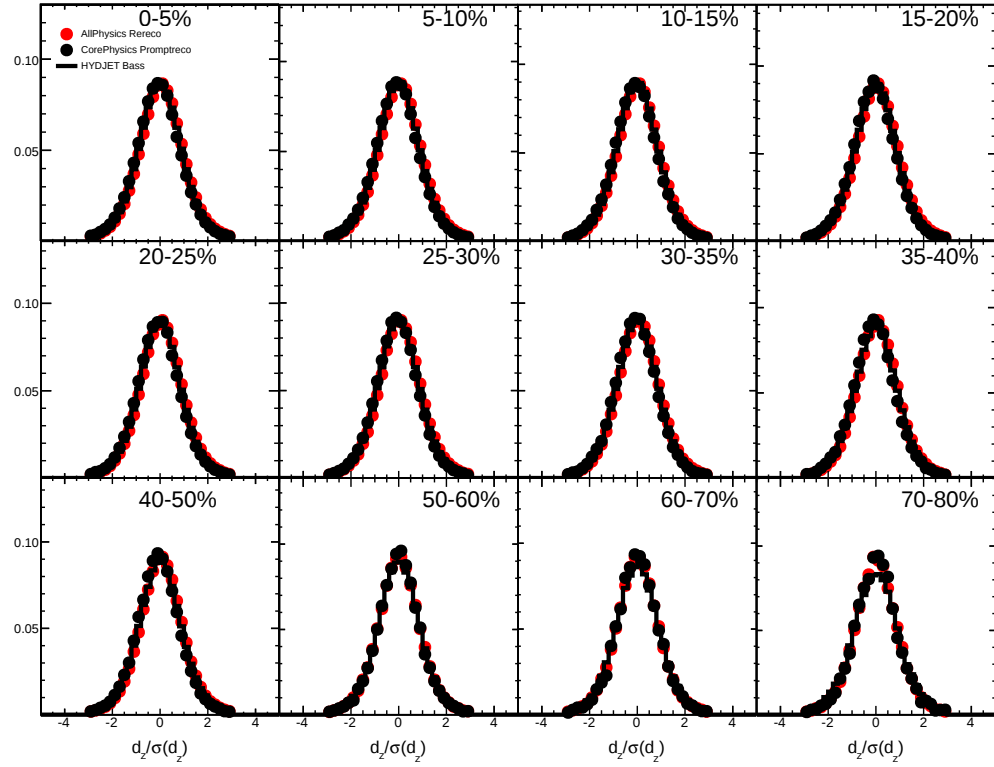
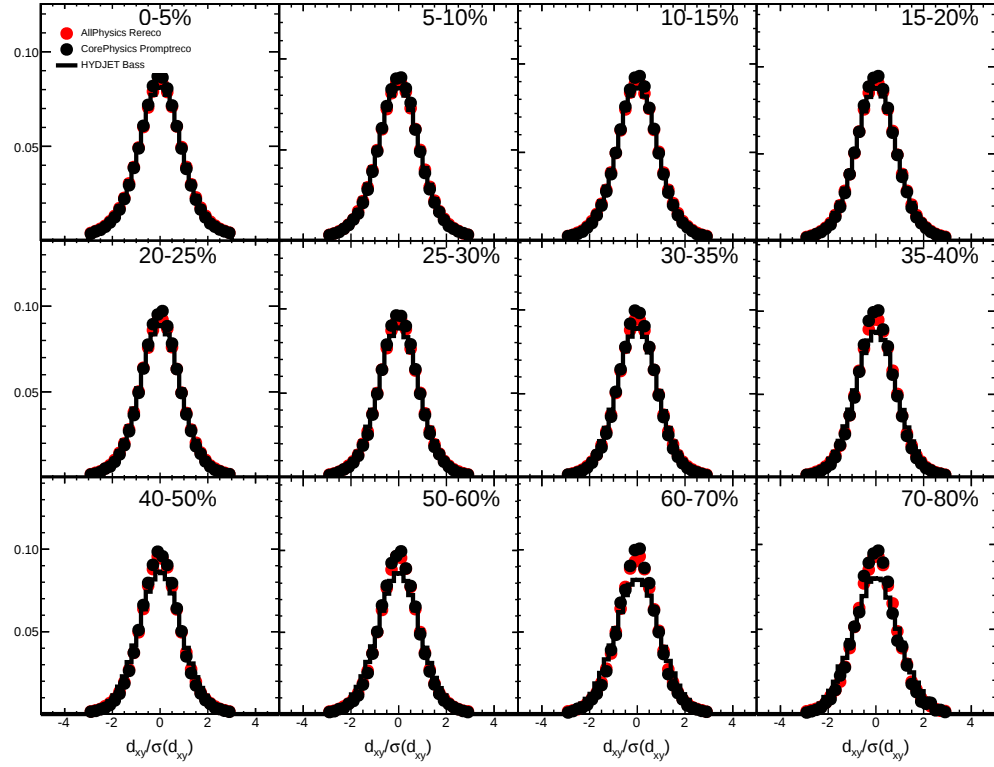


Figure 63. Number of valid hit distributions for the three data sets.

Appendix A (Continued)

Figure 64. $d_z/\sigma d_z$ distributions for the three data sets.

Appendix A (Continued)

Figure 65. $d_{xy}/\sigma d_{xy}$ distributions for the three data sets.

Appendix B

A PROOF OF THE LEAST-SQUARES FIT AND FOURIER COEFFICIENTS THEOREM

Theorem:

The best least-squares fit of a function, $f(x)$ composed of an arbitrary set of terms from an orthonormal basis, g_i , to a given function, $F(x)$, has fit parameters, c_i , equal to the Fourier coefficients, a_i for each i .

Proof:

Consider an arbitrary function, $F(x)$, expanded in an orthonormal basis, g_i , with the orthogonality condition given by:

$$\delta_{i,j} = \frac{1}{\lambda_i} \int_a^b g_i(x)g_j(x)dx$$

Then,

$$F(x) = \sum_{i=0}^{\infty} a_i g_i$$

where, a_i are the Fourier coefficients given by,

$$a_i = \frac{1}{\lambda_i} \int_a^b F(x)g_i dx$$

Appendix B (Continued)

Consider a function composed of an arbitrary subset of the functions $g_i(x)$:

$$f(x) = \sum_{i=\pi(1)}^{\pi(M)} c_i g_i(x)$$

where π is an arbitrary set of M unique positive integers $\{\pi(i) \mid 1 \leq i \leq M\}$.

To find the c_i that are the least squares fit coefficients, we need to minimize this expression:

$$m = \int_a^b \left[F(x) - \sum_{i=\pi(1)}^{\pi(M)} c_i g_i(x) \right]^2 dx$$

Some algebra...

$$m = \int_a^b F^2(x) dx - 2 \sum_{i=\pi(1)}^{\pi(M)} c_i \int_a^b F(x) g_i(x) dx + \sum_{i=\pi(1)}^{\pi(M)} \sum_{j=\pi(1)}^{\pi(M)} c_i c_j \int_a^b g_i(x) g_j(x) dx$$

$$m = \int_a^b F^2(x) dx - 2 \sum_{i=\pi(1)}^{\pi(M)} c_i \int_a^b \sum_{j=0}^{\infty} a_j g_j g_i(x) dx + \sum_{i=\pi(1)}^{\pi(M)} \sum_{j=\pi(1)}^{\pi(M)} c_i c_j \lambda_i \delta_{i,j}$$

$$m = \int_a^b F^2(x) dx - 2 \sum_{i=\pi(1)}^{\pi(M)} \lambda_i a_i c_i + \sum_{i=\pi(1)}^{\pi(M)} \lambda_i c_i^2 + \sum_{i=\pi(1)}^{\pi(M)} \lambda_i a_i^2 - \sum_{i=\pi(1)}^{\pi(M)} \lambda_i a_i^2$$

Appendix B (Continued)

$$m = \int_a^b F^2(x)dx - \sum_{j=\pi(1)}^{\pi(M)} \lambda_i a_i^2 + \sum_{i=\pi(1)}^{\pi(M)} \lambda_i (a_i - c_i)^2$$

This last expression is at minimum when each $c_i = a_i$ for each i in the set π .

Thus, the Fourier coefficients are equal to the least-squares fit coefficients independent of which terms are included in the fit.

Appendix C

2D CORRELATION FUNCTIONS

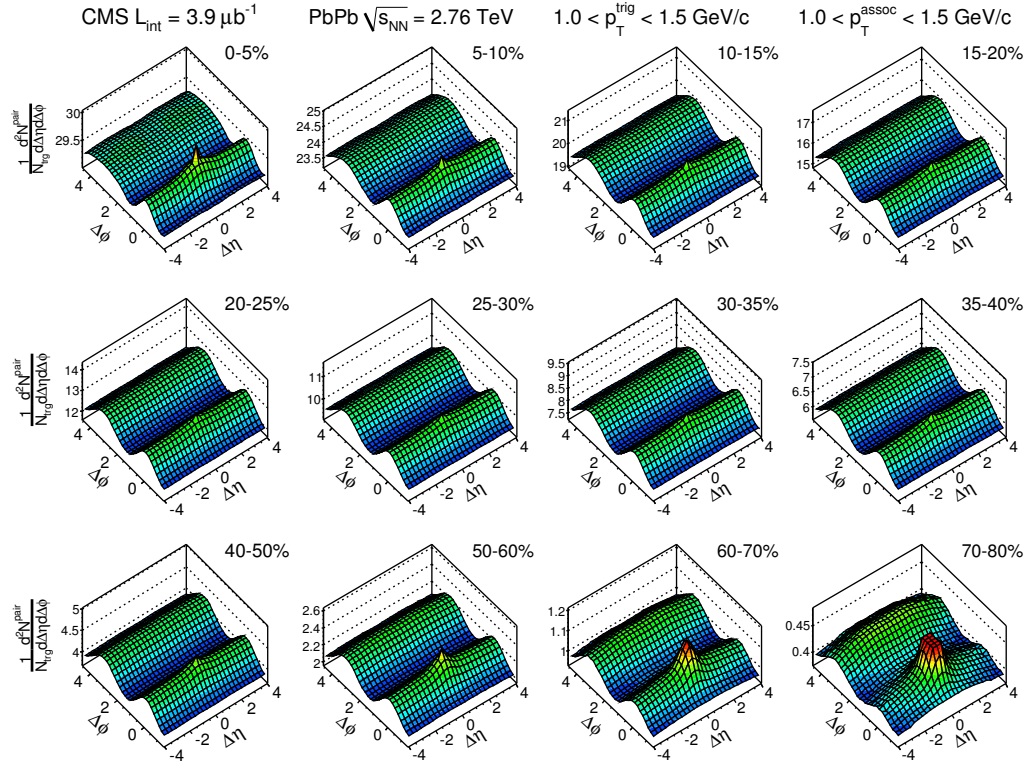


Figure 66. Two-dimensional per-trigger-particle associated yield
 $1 < p_{\text{T}}^{\text{trig}} < 1.5 \text{ GeV/c}$ with $1 < p_{\text{T}}^{\text{assoc}} < 1.5 \text{ GeV/c}$.

Appendix C (Continued)

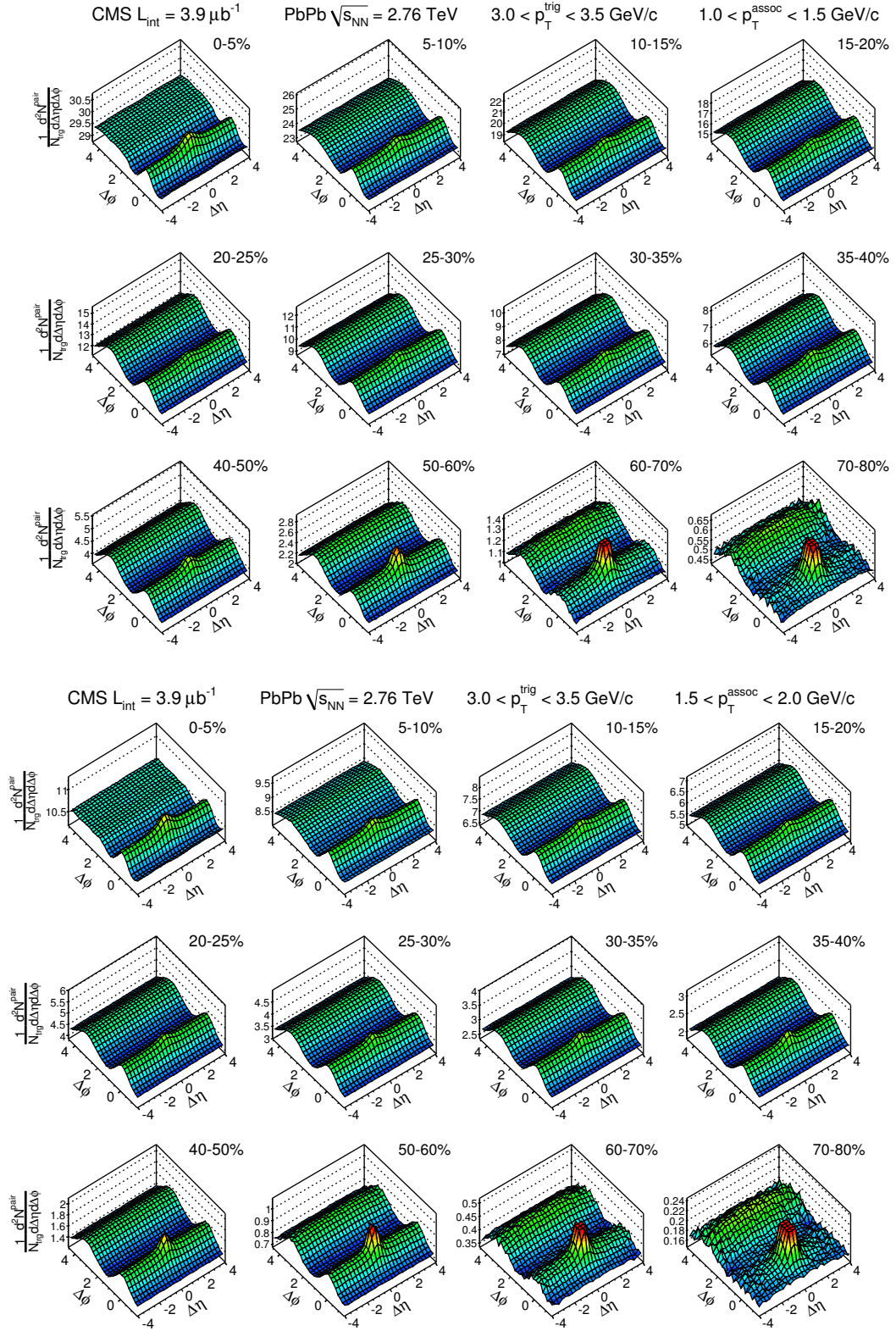


Figure 67. Two-dimensional per-trigger-particle associated yield $3 < p_T^{trig} < 3.5$ GeV/c with $1 < p_T^{assoc} < 1.5$ (top) and $1.5 < p_T^{assoc} < 2$ GeV/c (bottom).

Appendix C (Continued)

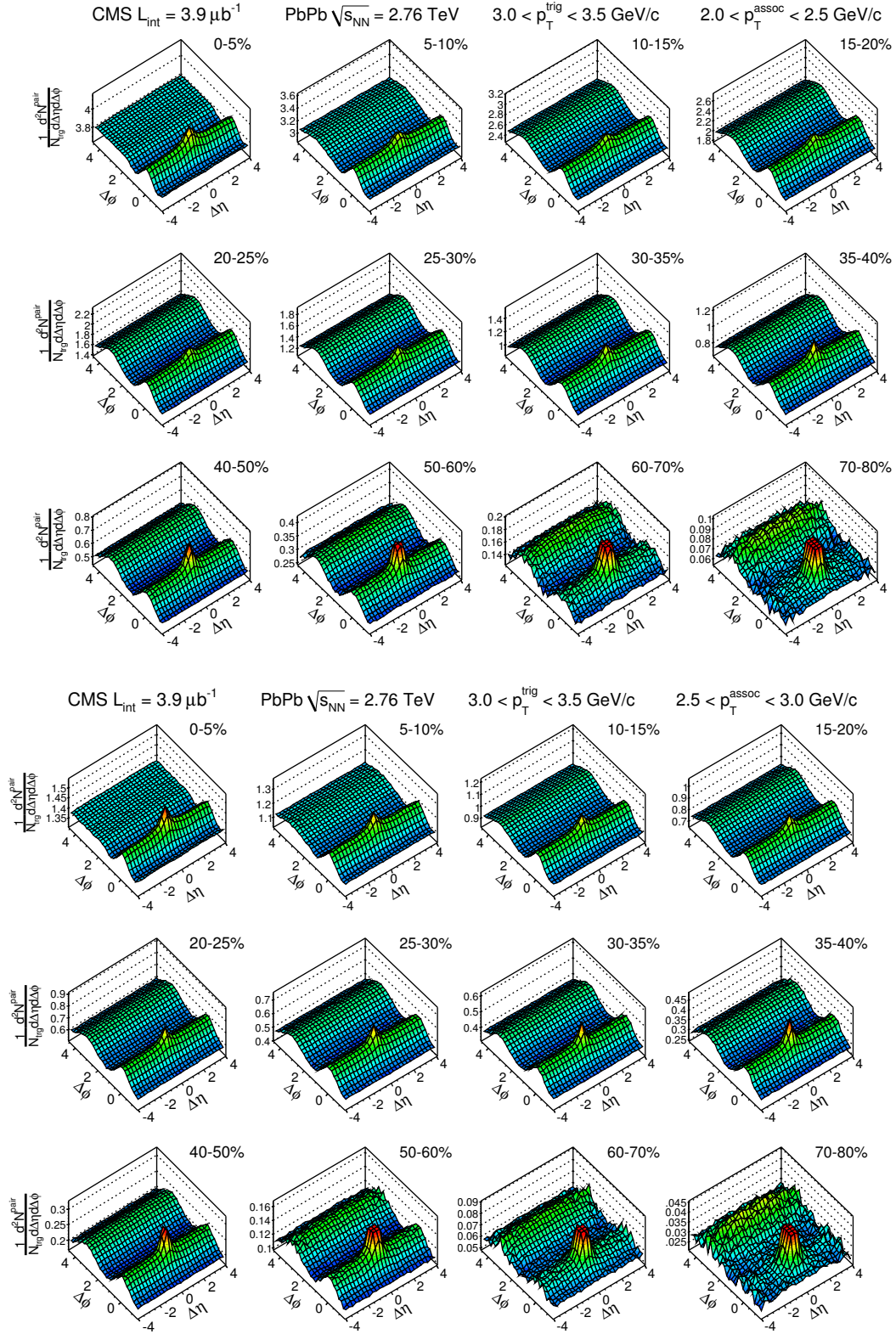


Figure 68. Two-dimensional per-trigger-particle associated yield $3 < p_T^{\text{trig}} < 3.5$ GeV/c with $2 < p_T^{\text{assoc}} < 2.5$ (top) and $2.5 < p_T^{\text{assoc}} < 3$ GeV/c (bottom).

Appendix C (Continued)

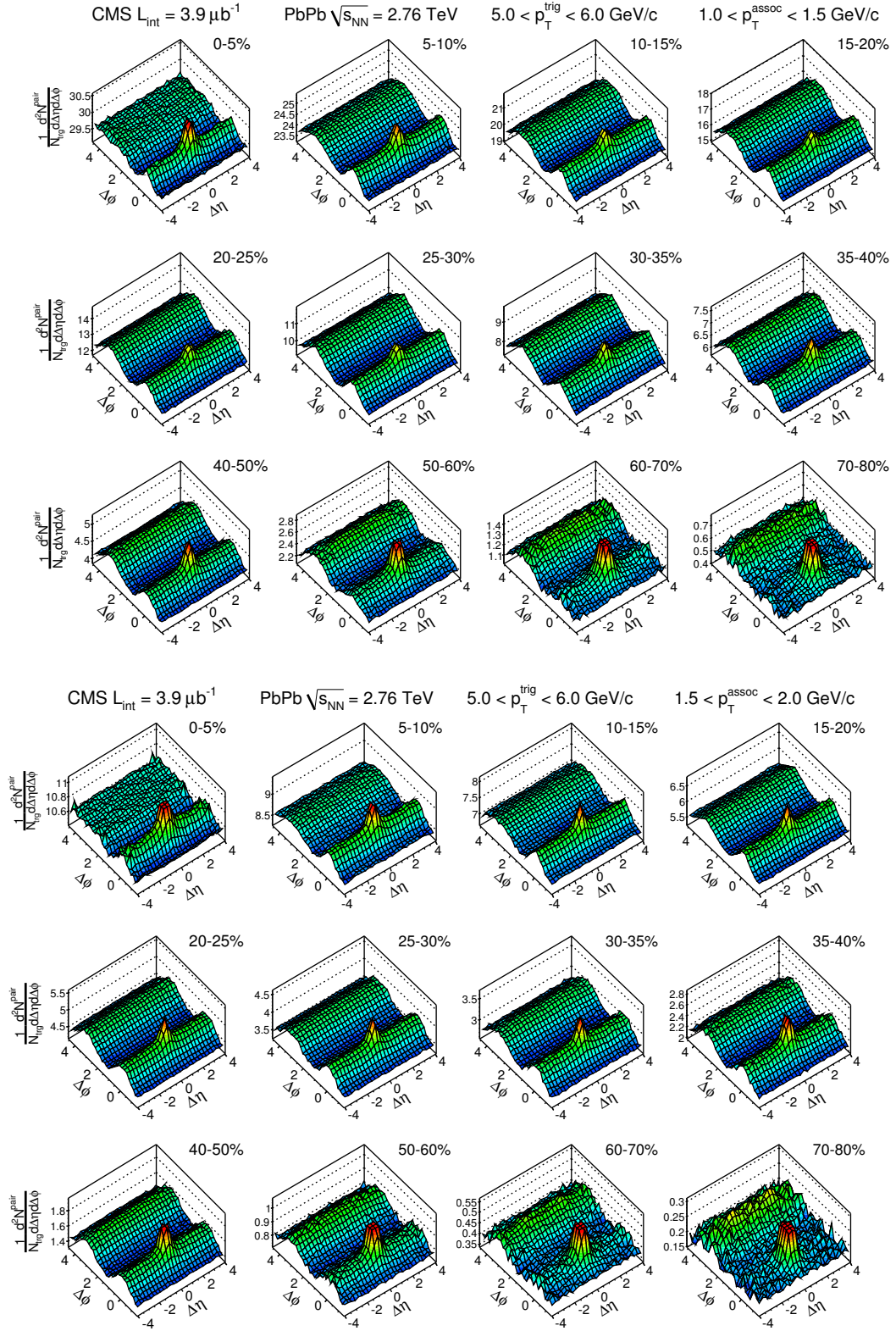


Figure 69. Two-dimensional per-trigger-particle associated yield $5 < p_T^{\text{trig}} < 6$ GeV/c with $1 < p_T^{\text{assoc}} < 1.5$ (top) and $1.5 < p_T^{\text{assoc}} < 2$ GeV/c (bottom).

Appendix C (Continued)

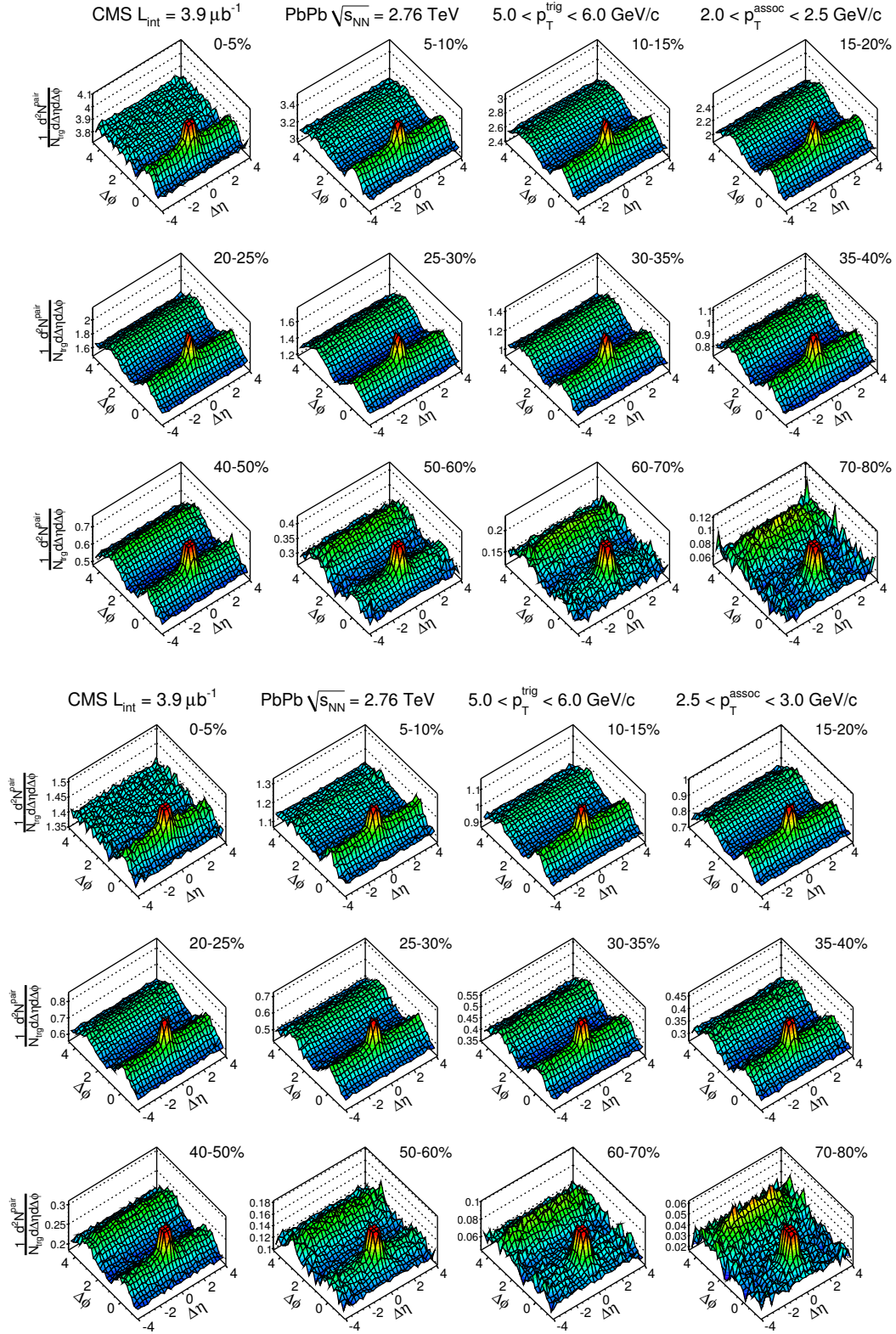


Figure 70. Two-dimensional per-trigger-particle associated yield $5 < p_T^{trig} < 6$ GeV/c with $2 < p_T^{assoc} < 2.5$ (top) and $2.5 < p_T^{assoc} < 3$ GeV/c (bottom).

Appendix C (Continued)

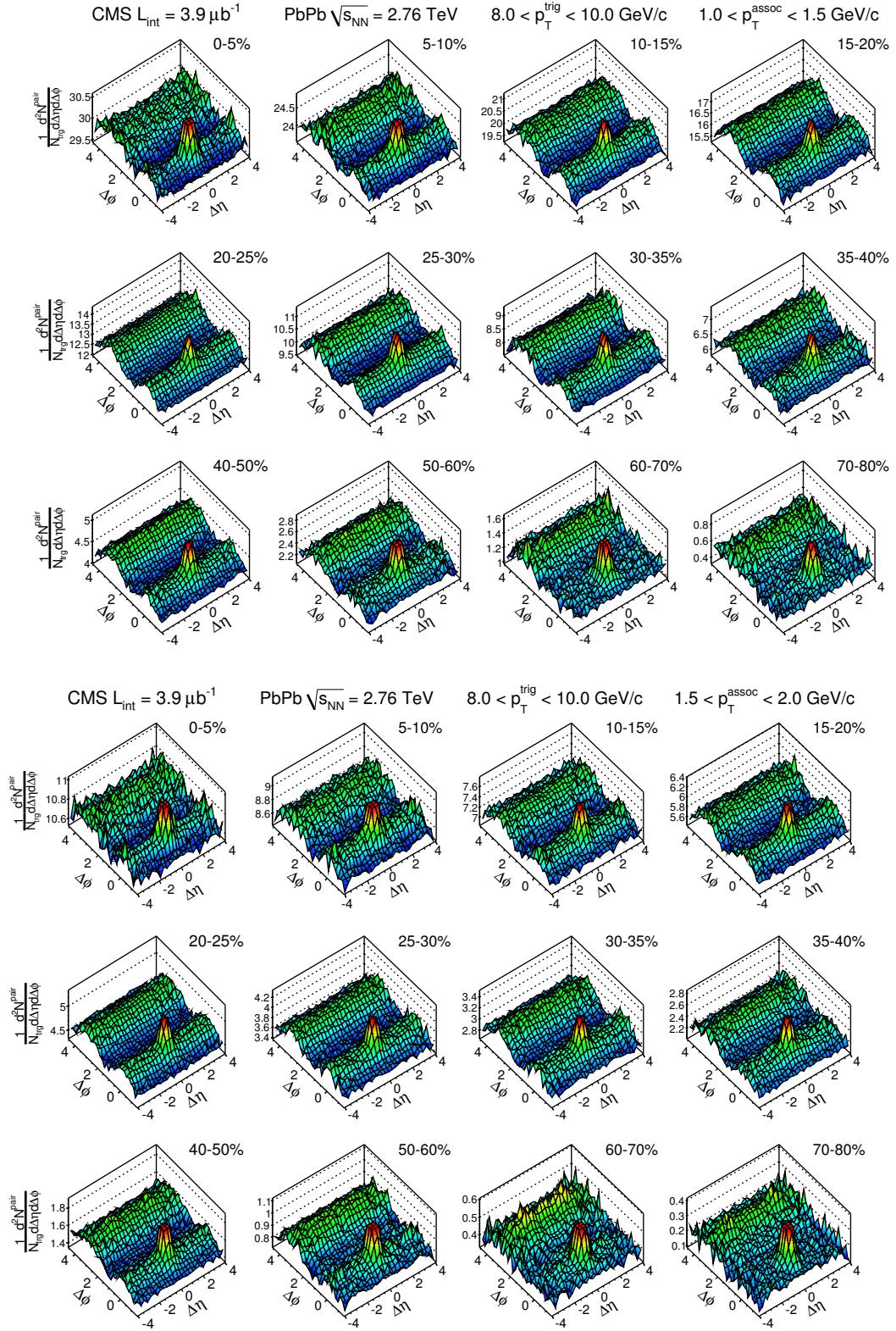


Figure 71. Two-dimensional per-trigger-particle associated yield $8 < p_T^{\text{trig}} < 10$ GeV/c with $1 < p_T^{\text{assoc}} < 1.5$ (top) and $1.5 < p_T^{\text{assoc}} < 2$ GeV/c (bottom).

Appendix C (Continued)

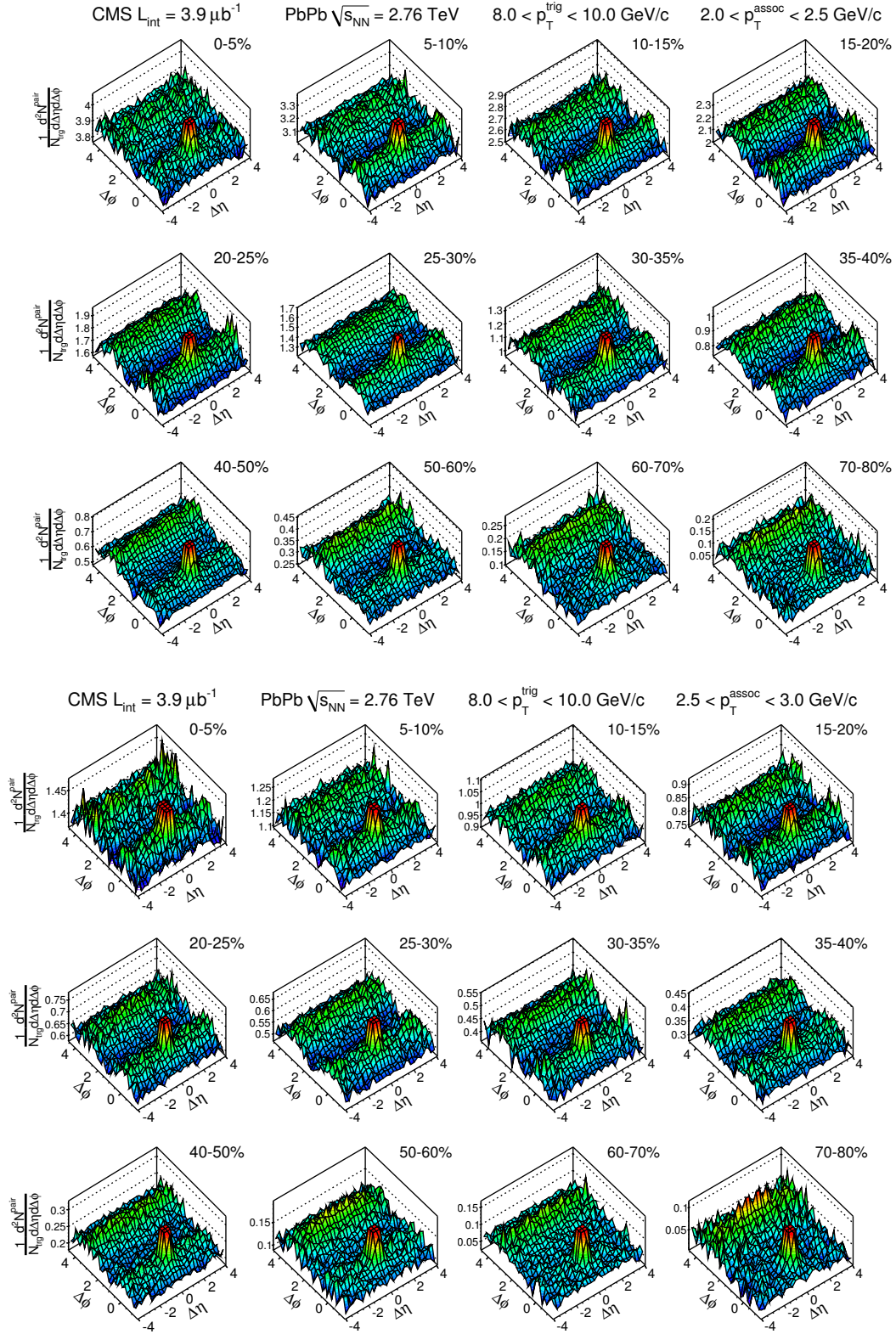


Figure 72. Two-dimensional per-trigger-particle associated yield $8 < p_T^{\text{trig}} < 10$ GeV/c with $2 < p_T^{\text{assoc}} < 2.5$ (top) and $2.5 < p_T^{\text{assoc}} < 3$ GeV/c (bottom).

Appendix D

1D JET AND RIDGE REGION PROJECTIONS

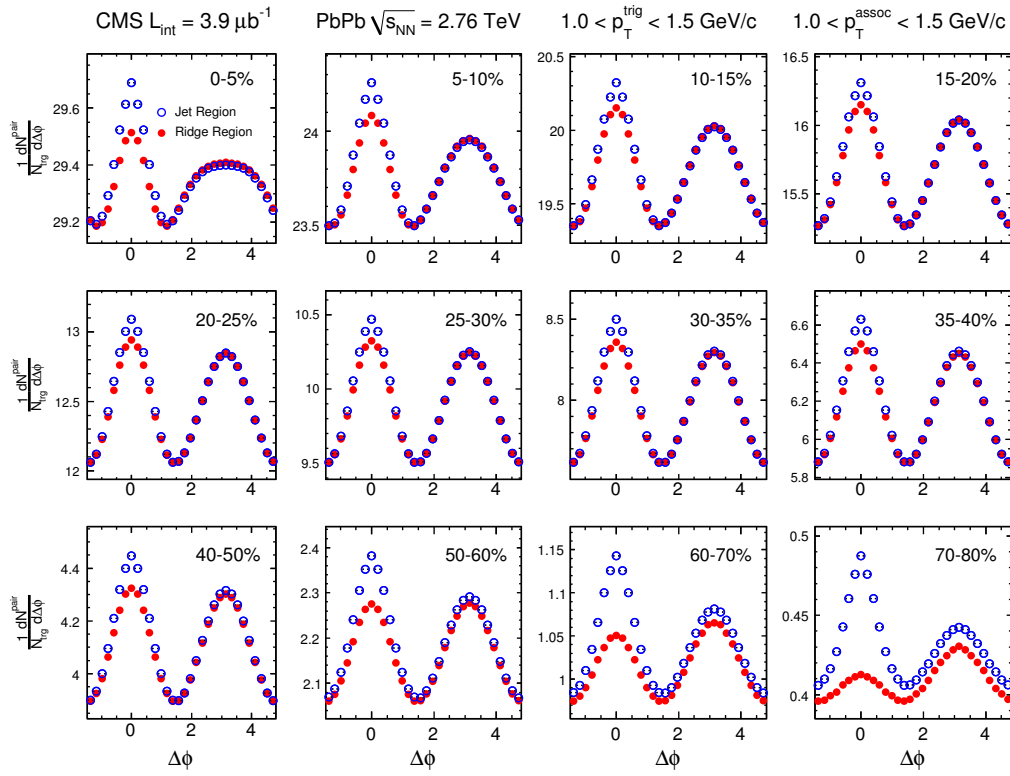


Figure 73. One-dimensional $\Delta\phi$ projections for jet and ridge region $1 < p_{\text{T}}^{\text{trig}} < 1.5 \text{ GeV/c}$ and $1 < p_{\text{T}}^{\text{assoc}} < 1.5 \text{ GeV/c}$.

Appendix D (Continued)

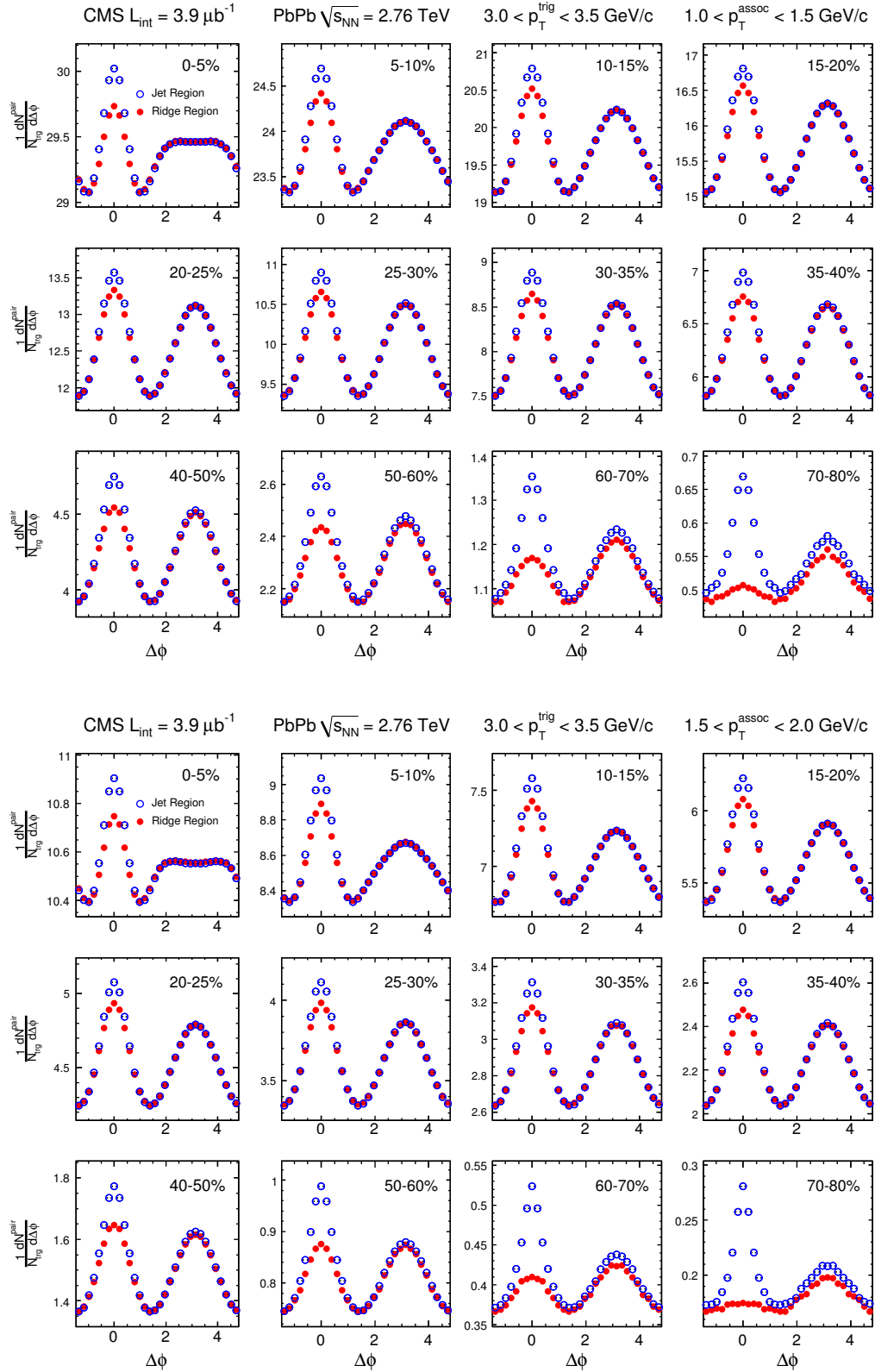


Figure 74. One-dimensional $\Delta\phi$ projections for jet and ridge region $3 < p_T^{\text{trig}} < 3.5$ GeV/c with $1 < p_T^{\text{assoc}} < 1.5$ (top) and $1.5 < p_T^{\text{assoc}} < 2$ GeV/c (bottom).

Appendix D (Continued)

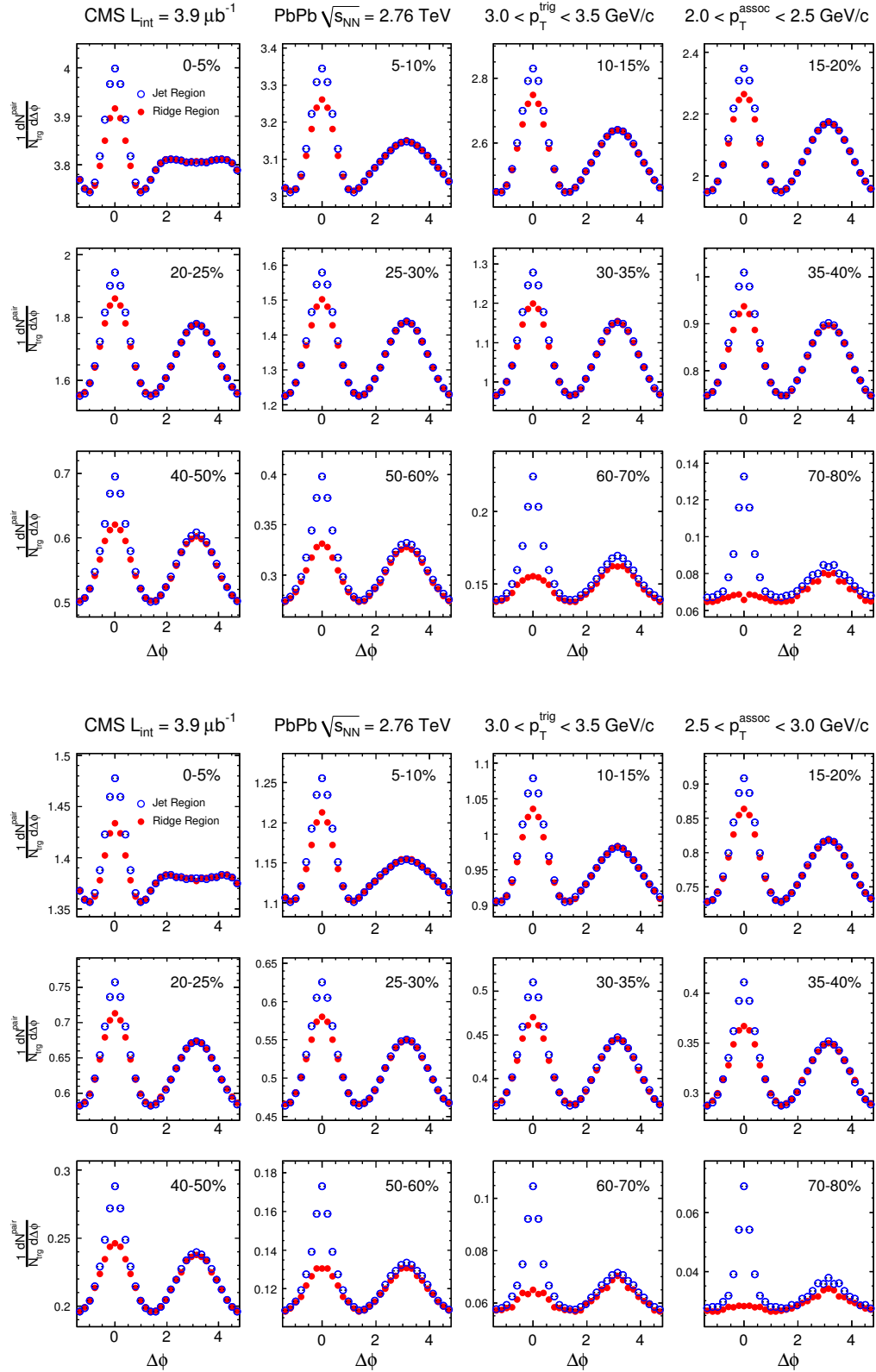


Figure 75. One-dimensional $\Delta\phi$ projections for jet and ridge region $3 < p_T^{\text{trig}} < 3.5$ GeV/c with $2 < p_T^{\text{assoc}} < 2.5$ (top) and $2.5 < p_T^{\text{assoc}} < 3$ GeV/c (bottom).

Appendix D (Continued)

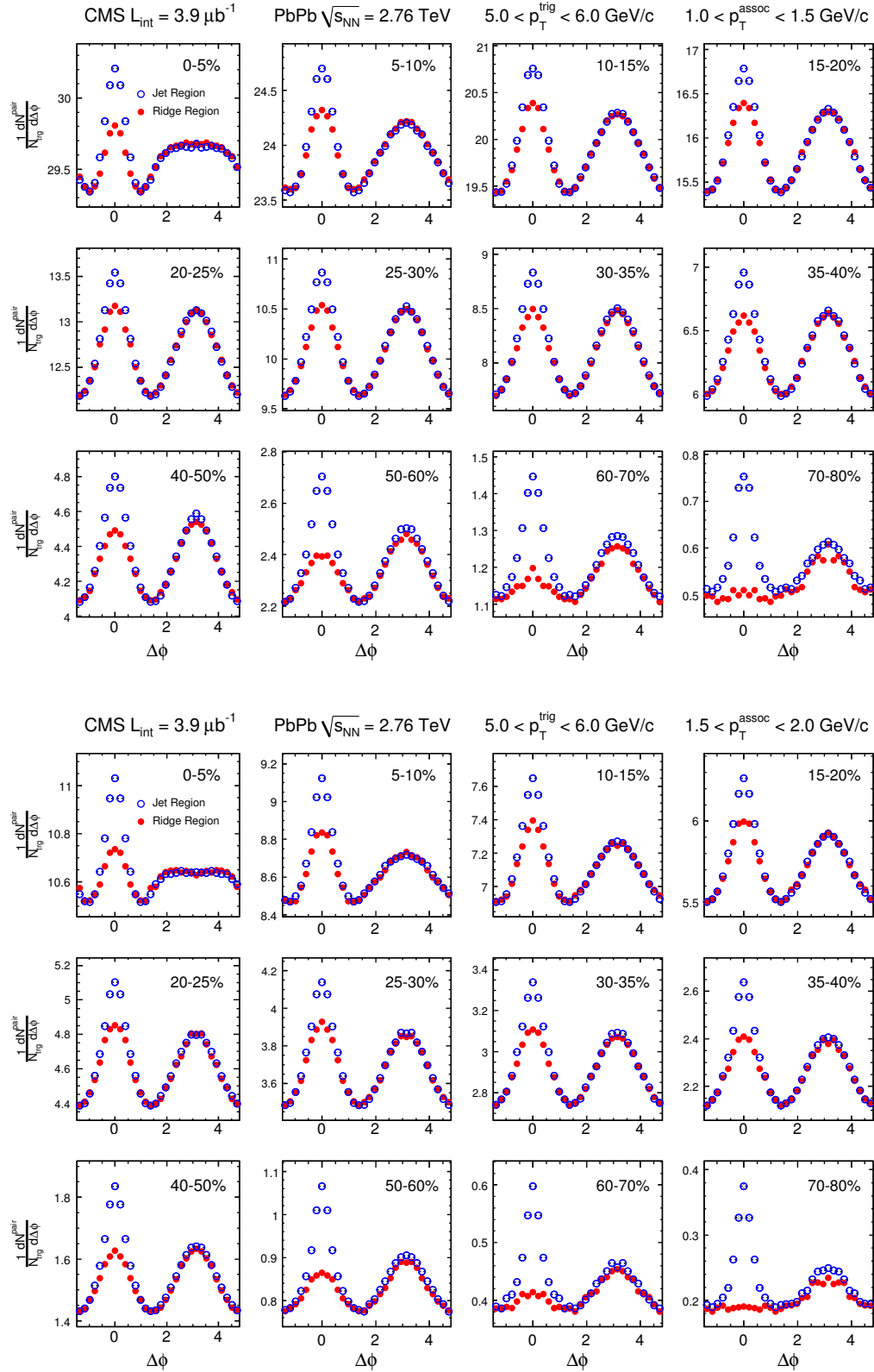


Figure 76. One-dimensional $\Delta\phi$ projections for jet and ridge region $5 < p_{\text{T}}^{\text{trig}} < 6 \text{ GeV/c}$ with $1 < p_{\text{T}}^{\text{assoc}} < 1.5$ (top) and $1.5 < p_{\text{T}}^{\text{assoc}} < 2 \text{ GeV/c}$ (bottom).

Appendix D (Continued)

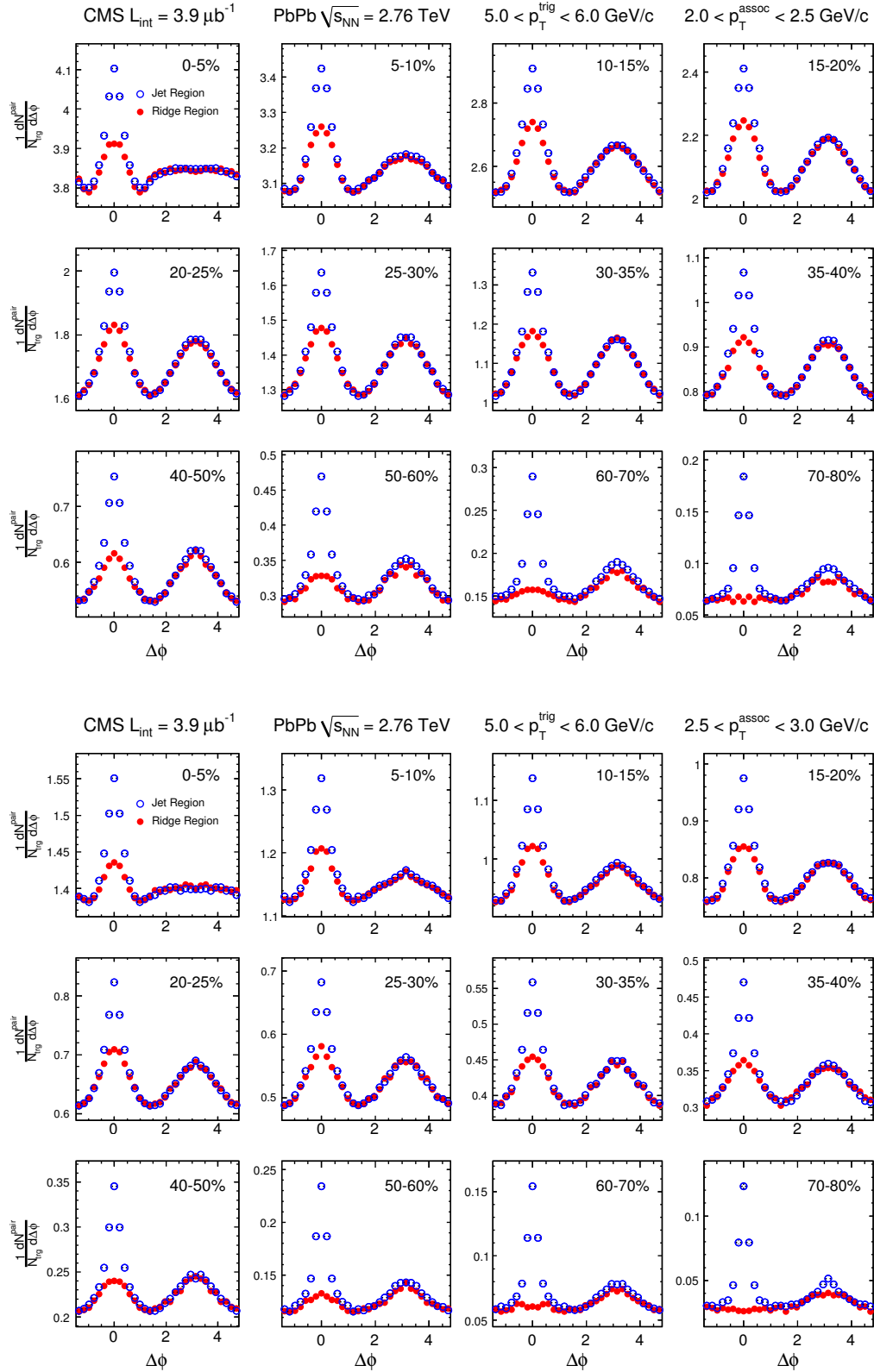


Figure 77. One-dimensional $\Delta\phi$ projections for jet and ridge region $5 < p_{\text{T}}^{\text{trig}} < 6$ GeV/c with $2 < p_{\text{T}}^{\text{assoc}} < 2.5$ (top) and $2.5 < p_{\text{T}}^{\text{assoc}} < 3$ GeV/c (bottom).

Appendix D (Continued)

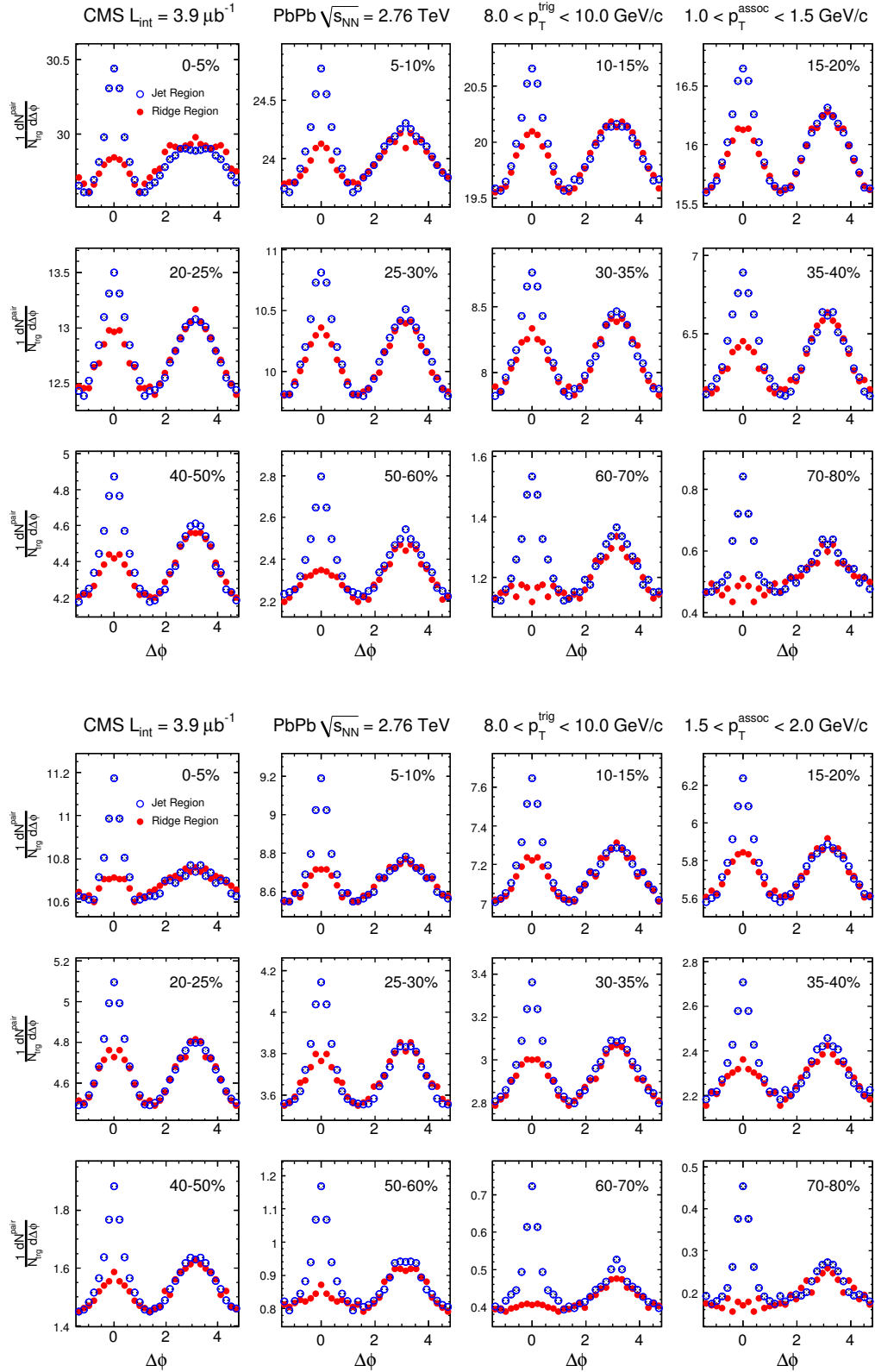


Figure 78. One-dimensional $\Delta\phi$ projections for jet and ridge region $8 < p_T^{\text{trig}} < 10$ GeV/c with $1 < p_T^{\text{assoc}} < 1.5$ (top) and $1.5 < p_T^{\text{assoc}} < 2$ GeV/c (bottom).

Appendix D (Continued)

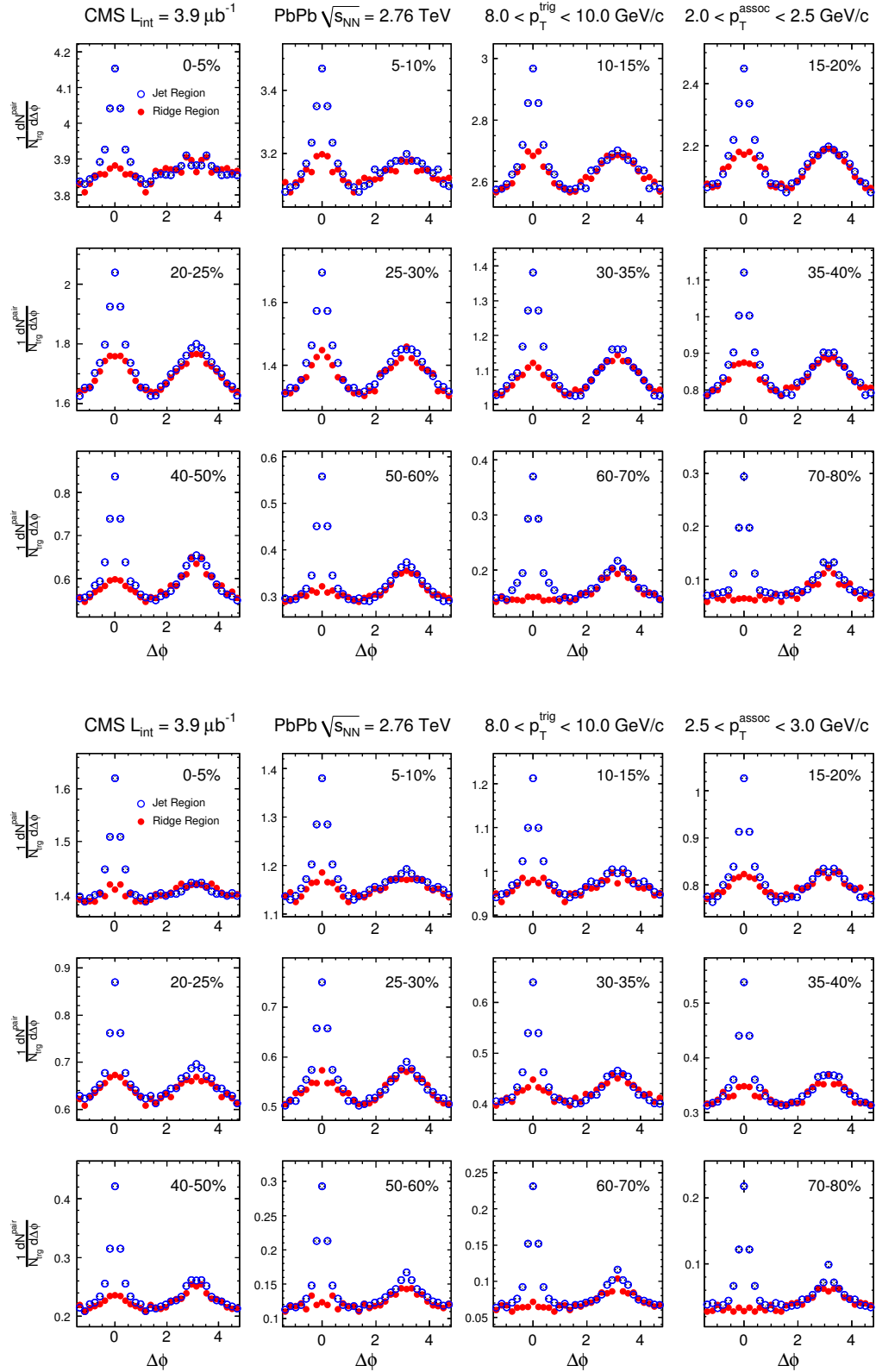


Figure 79. One-dimensional $\Delta\phi$ projections for jet and ridge region $8 < p_T^{\text{trig}} < 10$ GeV/c with $2 < p_T^{\text{assoc}} < 2.5$ (top) and $2.5 < p_T^{\text{assoc}} < 3$ GeV/c (bottom).

Appendix E

1D PROJECTIONS JET MINUS RIDGE REGION

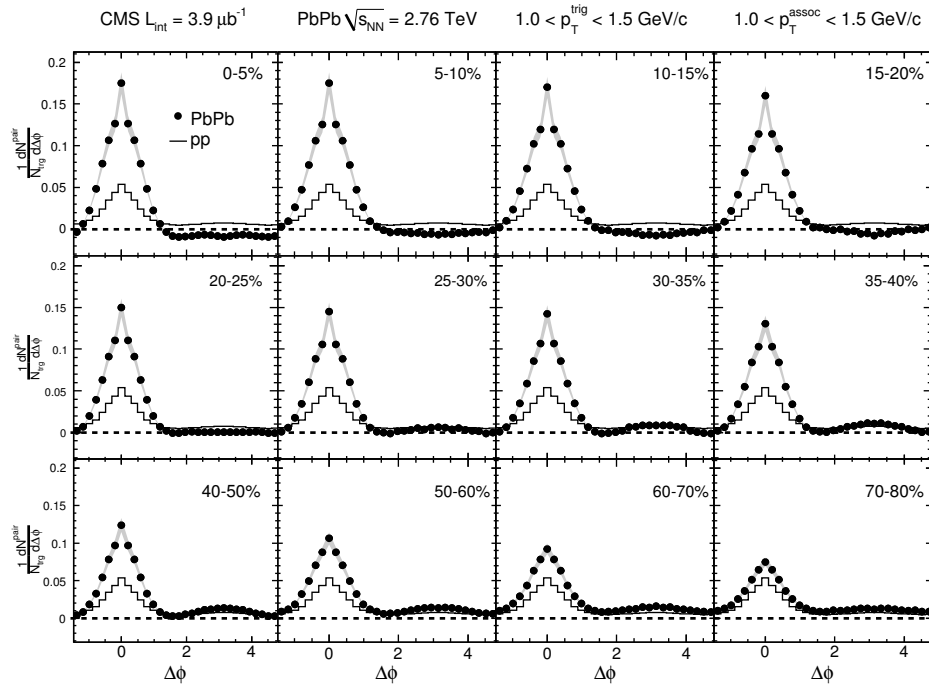


Figure 80. One-dimensional $\Delta\phi$ projections for jet minus ridge region $1 < p_{\text{T}}^{\text{trig}} < 1.5 \text{ GeV/c}$ and $1 < p_{\text{T}}^{\text{assoc}} < 1.5 \text{ GeV/c}$.

Appendix E (Continued)

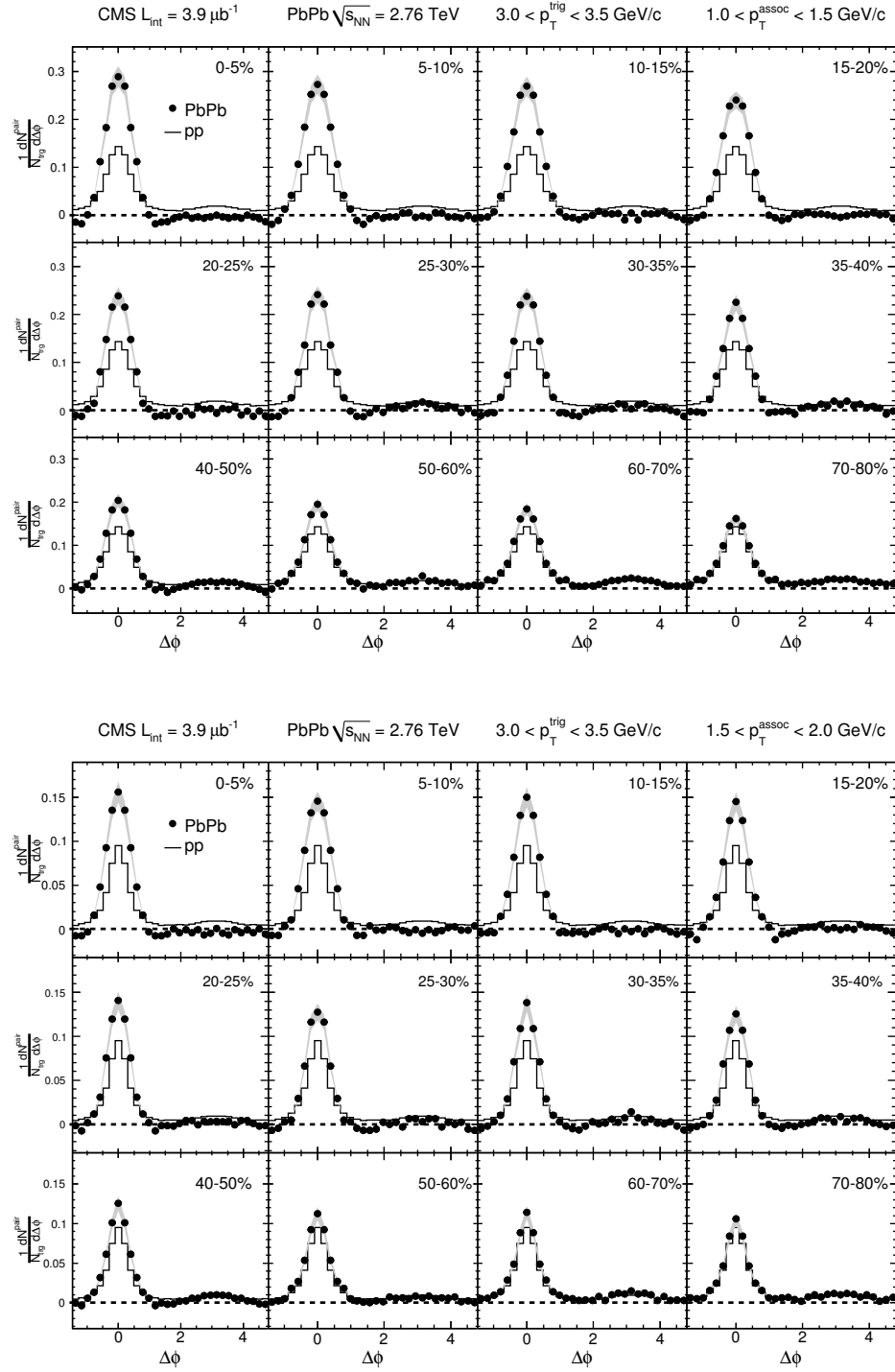


Figure 81. One-dimensional $\Delta\phi$ projections for jet minus ridge region $3 < p_{\text{T}}^{\text{trig}} < 3.5 \text{ GeV/c}$ with $1 < p_{\text{T}}^{\text{assoc}} < 1.5$ (top) and $1.5 < p_{\text{T}}^{\text{assoc}} < 2 \text{ GeV/c}$ (bottom).

Appendix E (Continued)

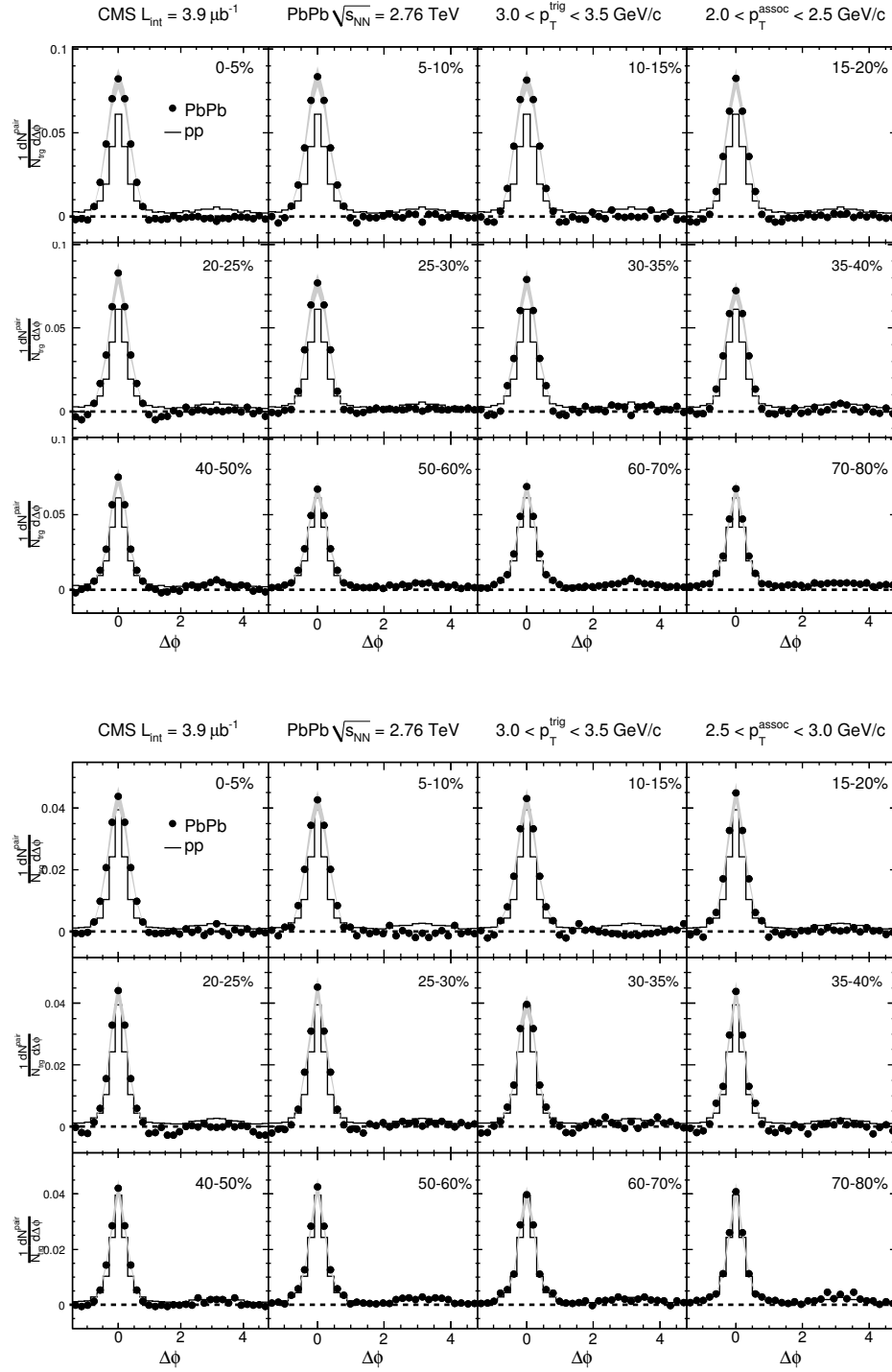


Figure 82. One-dimensional $\Delta\phi$ projections for jet minus ridge region $3 < p_{\text{T}}^{\text{trig}} < 3.5 \text{ GeV/c}$ with $2 < p_{\text{T}}^{\text{assoc}} < 2.5$ (top) and $2.5 < p_{\text{T}}^{\text{assoc}} < 3 \text{ GeV/c}$ (bottom).

Appendix E (Continued)

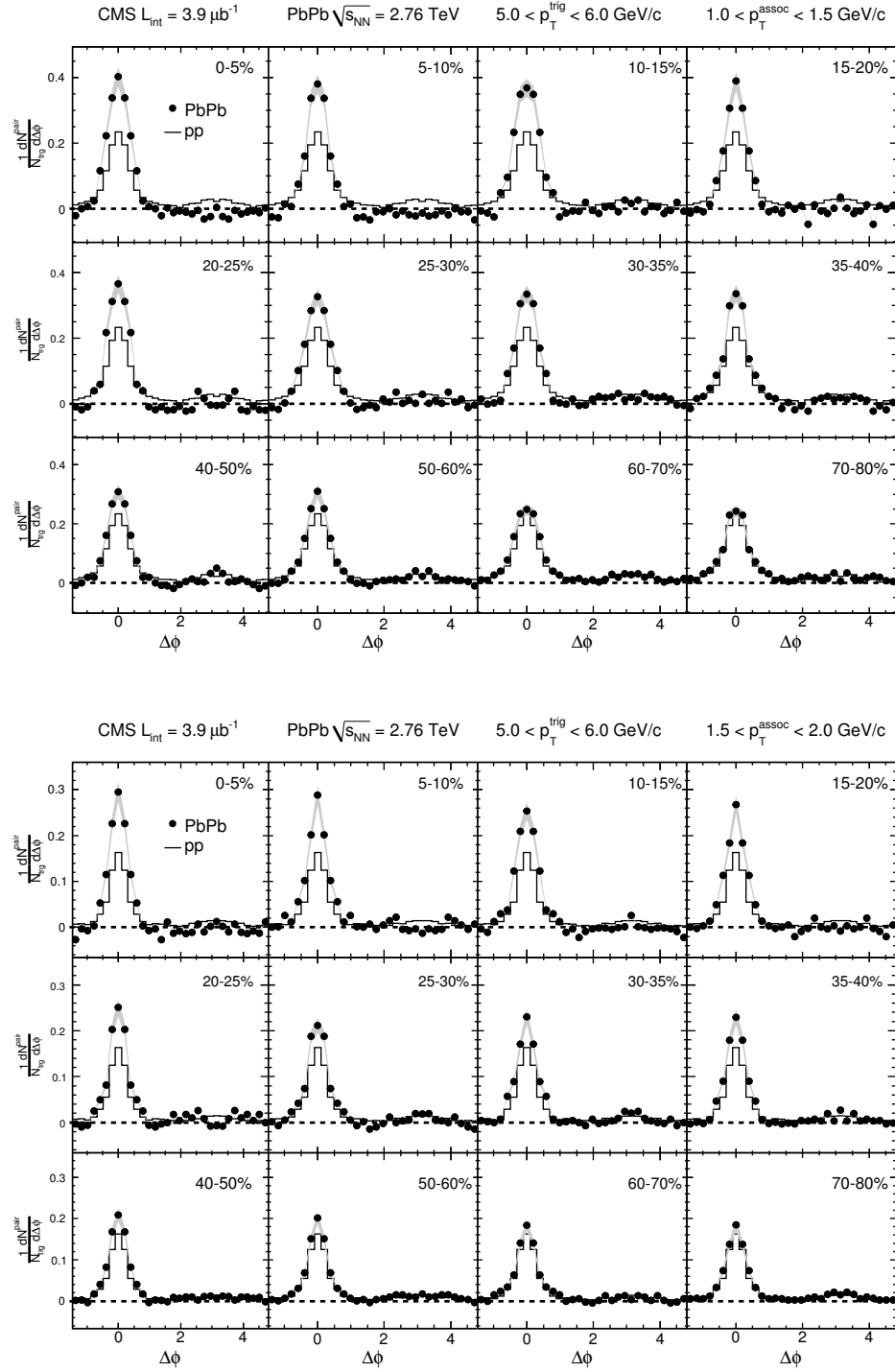


Figure 83. One-dimensional $\Delta\phi$ projections for jet minus ridge region $5 < p_{\text{T}}^{\text{trig}} < 6 \text{ GeV/c}$ with $1 < p_{\text{T}}^{\text{assoc}} < 1.5$ (top) and $1.5 < p_{\text{T}}^{\text{assoc}} < 2 \text{ GeV/c}$ (bottom).

Appendix E (Continued)

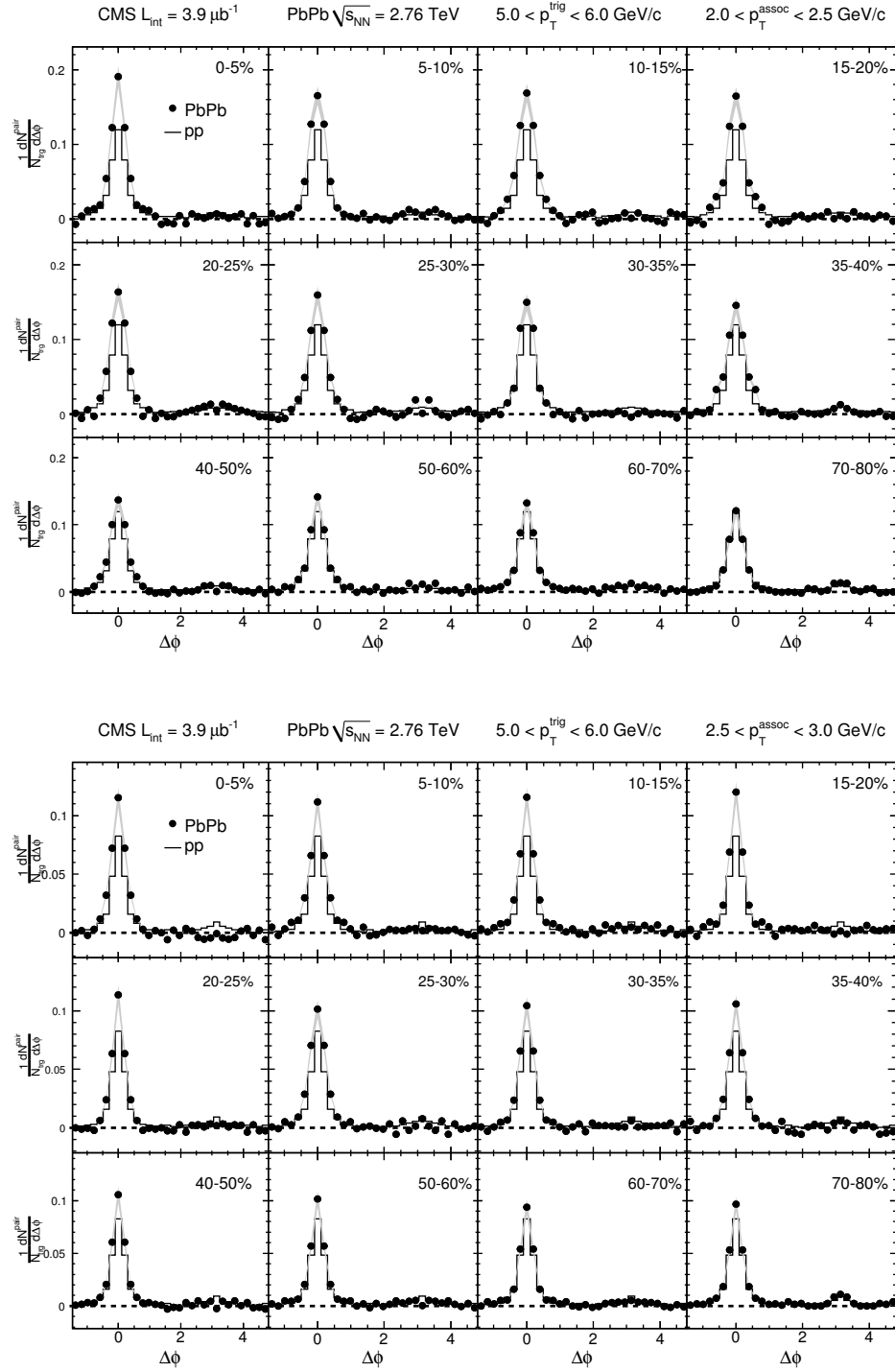


Figure 84. One-dimensional $\Delta\phi$ projections for jet minus ridge region $5 < p_{\text{T}}^{\text{trig}} < 6 \text{ GeV/c}$ with $2 < p_{\text{T}}^{\text{assoc}} < 2.5$ (top) and $2.5 < p_{\text{T}}^{\text{assoc}} < 3 \text{ GeV/c}$ (bottom).

Appendix E (Continued)

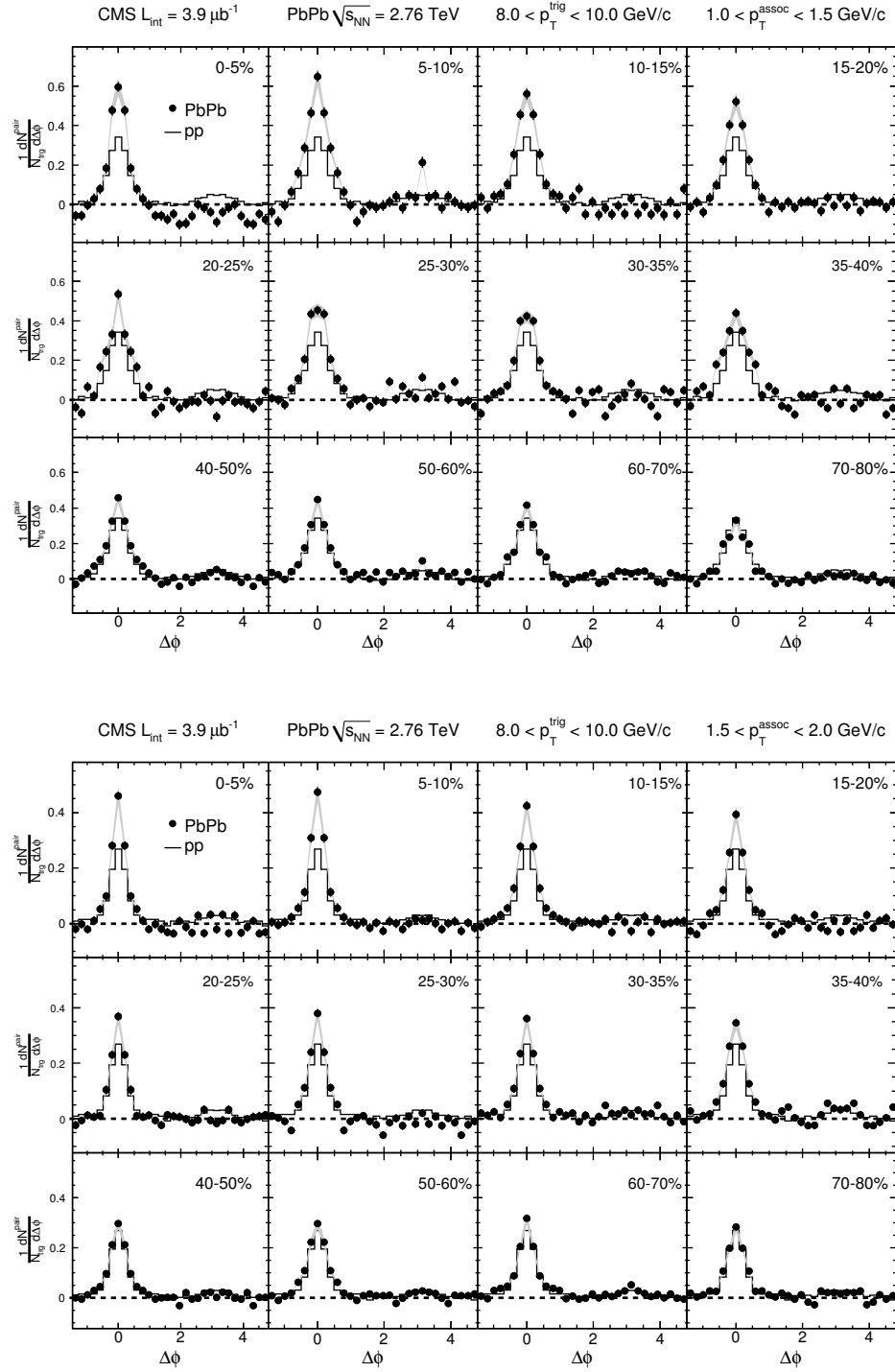


Figure 85. One-dimensional $\Delta\phi$ projections for jet minus ridge region $8 < p_{\text{T}}^{\text{trig}} < 10 \text{ GeV}/c$ with $1 < p_{\text{T}}^{\text{assoc}} < 1.5$ (top) and $1.5 < p_{\text{T}}^{\text{assoc}} < 2 \text{ GeV}/c$ (bottom).

Appendix E (Continued)

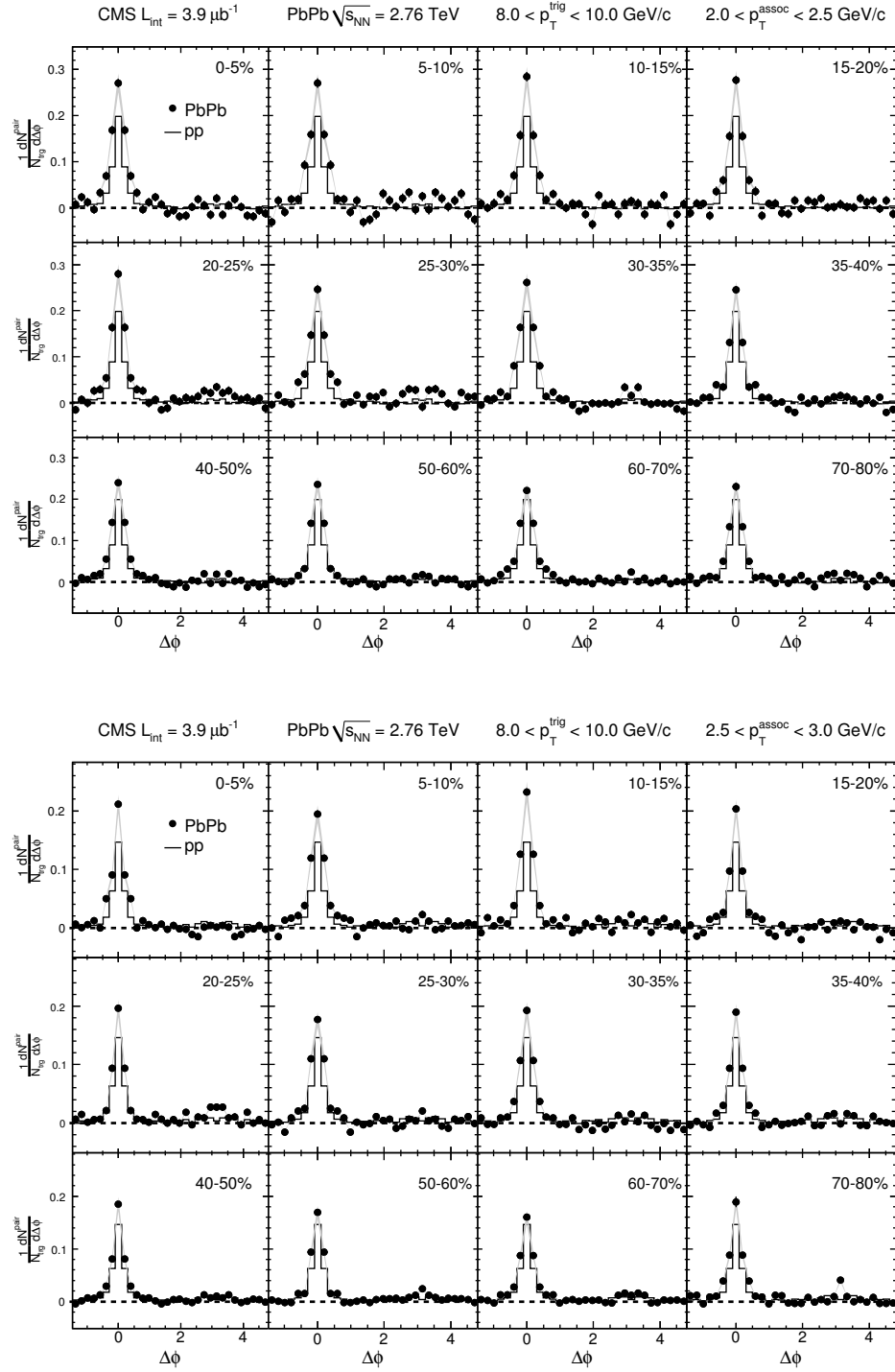


Figure 86. One-dimensional $\Delta\phi$ projections for jet minus ridge region $8 < p_{\text{T}}^{\text{trig}} < 10 \text{ GeV}/c$ with $2 < p_{\text{T}}^{\text{assoc}} < 2.5$ (top) and $2.5 < p_{\text{T}}^{\text{assoc}} < 3 \text{ GeV}/c$ (bottom).

Appendix F

YIELDS

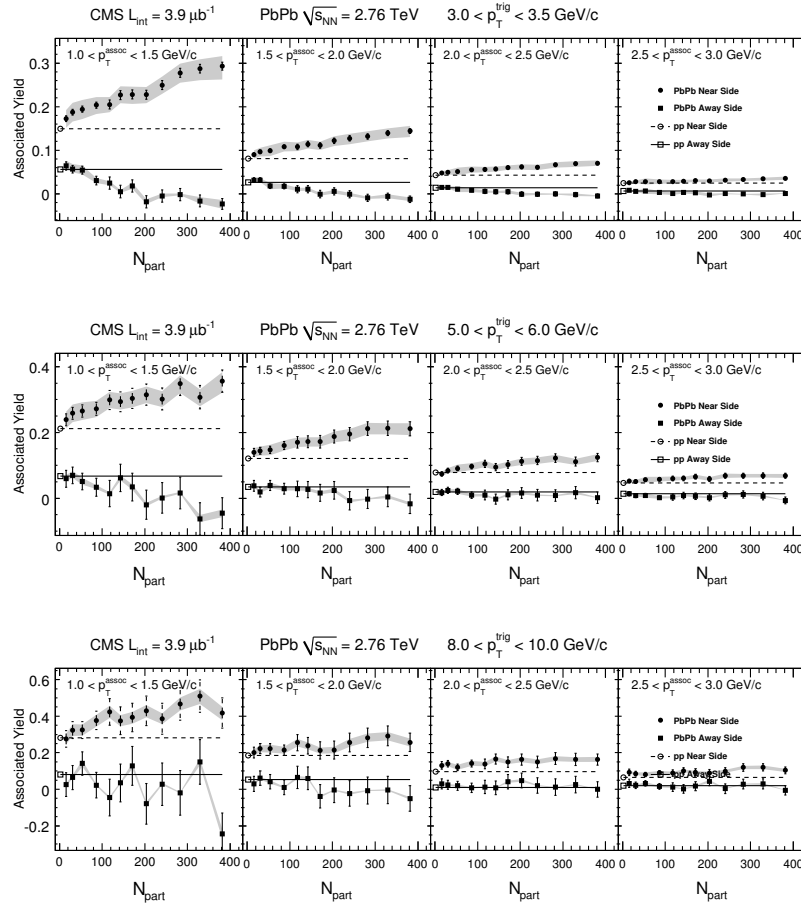


Figure 87. The integrated associated yields of the near-side peak ($|\Delta\phi| < 1.18$) and away-side region ($|\Delta\phi| > 1.18$), requiring $3 < p_T^{\text{trig}} < 3.5$ GeV/c (top), $5 < p_T^{\text{trig}} < 6$ (middle), and $8 < p_T^{\text{trig}} < 10$ (bottom) for four different intervals of p_T^{assoc} , as a function of N_{part} in PbPb collisions at $\sqrt{s_{NN}} = 2.76$ TeV. The error bars correspond to statistical uncertainties only, and are too small to be seen for most points, while the grey bands denote the systematic uncertainties. The lines show the results from pp collisions at $\sqrt{s} = 2.76$ TeV.

Appendix G

1D JET AND RIDGE REGION FLOW SUBTRACTED PROJECTIONS

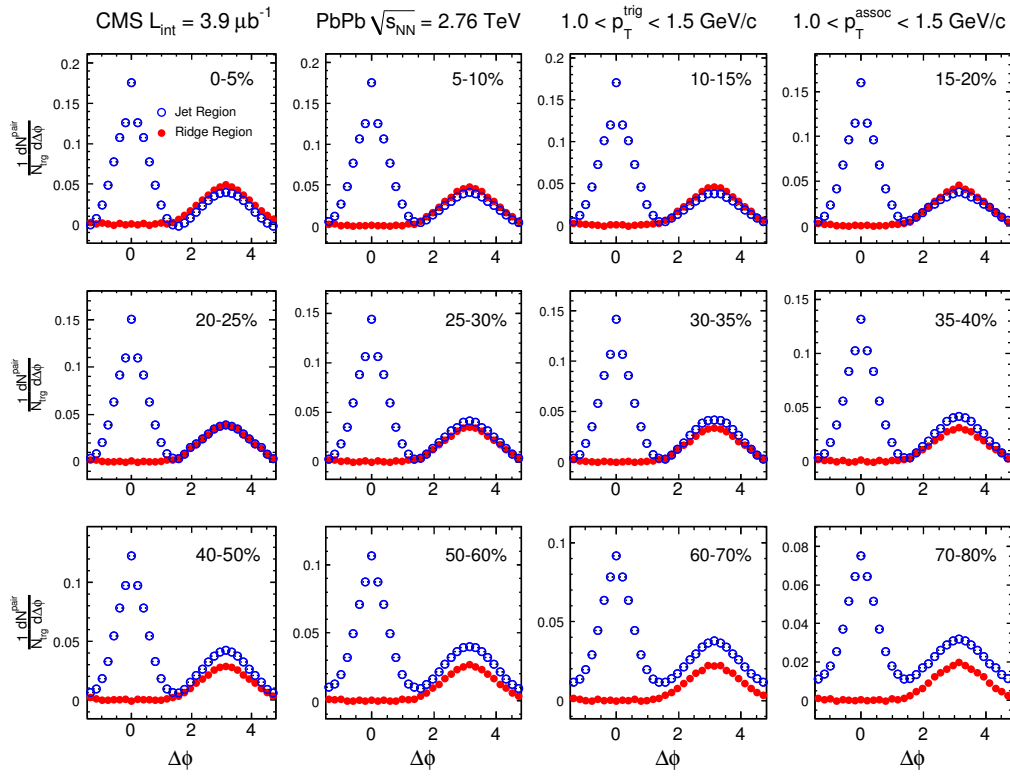


Figure 88. Flow-subtracted one-dimensional $\Delta\phi$ projections for jet and ridge region
 $1 < p_{\text{T}}^{\text{trig}} < 1.5 \text{ GeV}/c$ and $1 < p_{\text{T}}^{\text{assoc}} < 1.5 \text{ GeV}/c$.

Appendix G (Continued)

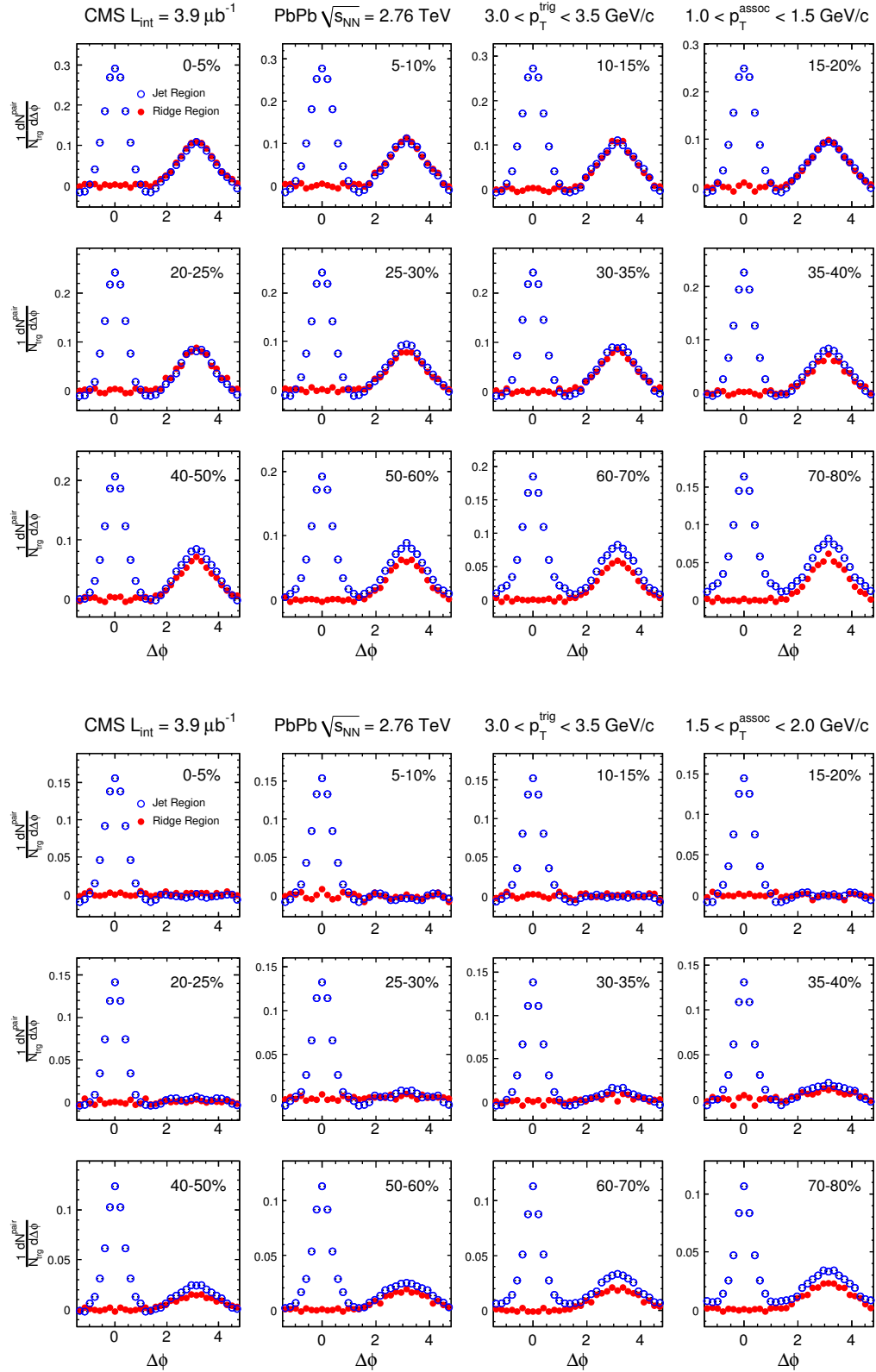


Figure 89. Flow-subtracted one-dimensional $\Delta\phi$ projections for jet and ridge region $3 < p_T^{\text{trig}} < 3.5$ GeV/c with $1 < p_T^{\text{assoc}} < 1.5$ (top) and $1.5 < p_T^{\text{assoc}} < 2$ GeV/c (bottom).

Appendix G (Continued)

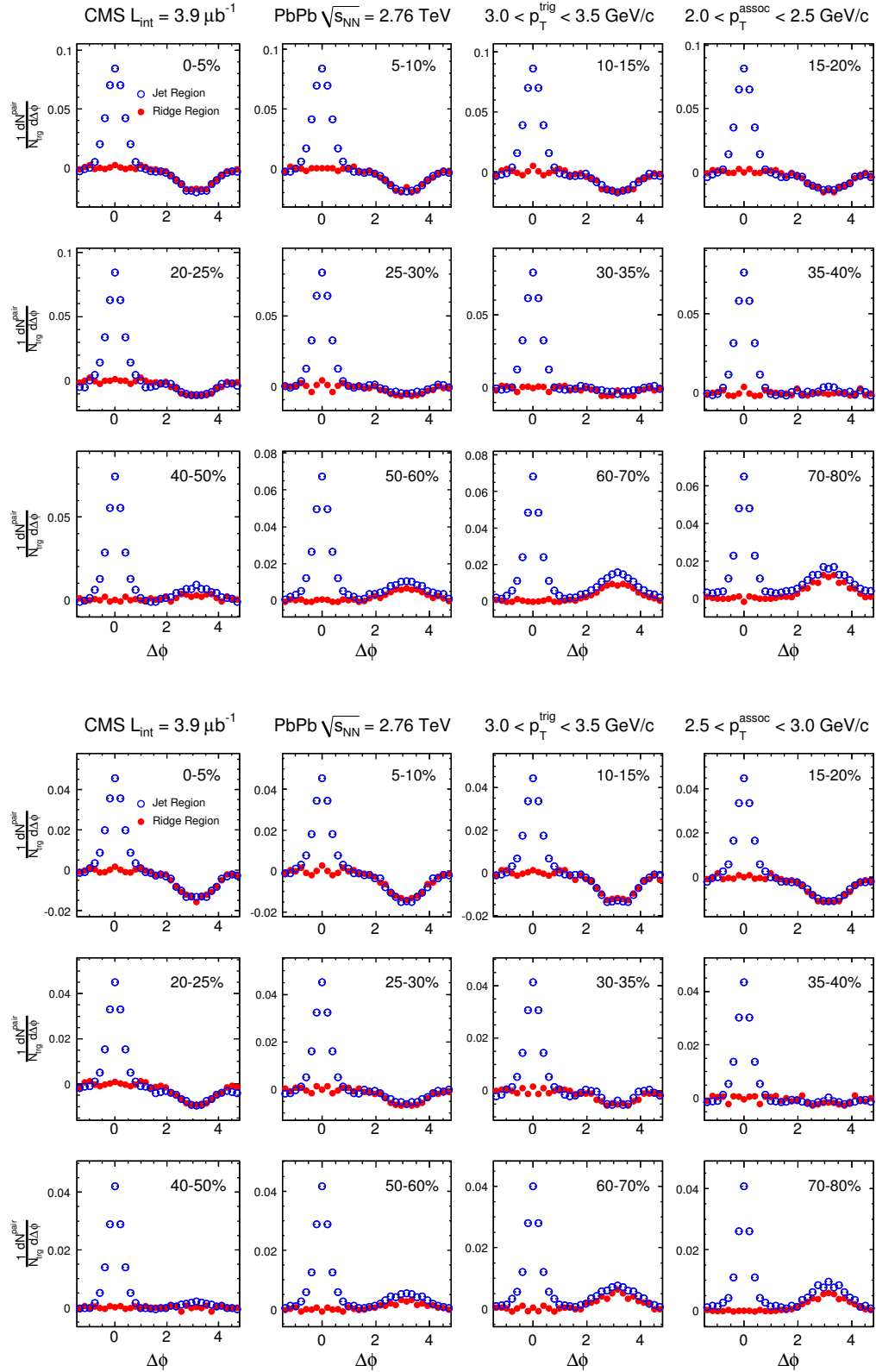


Figure 90. Flow-subtracted one-dimensional $\Delta\phi$ projections for jet and ridge region $3 < p_T^{\text{trig}} < 3.5 \text{ GeV/c}$ with $2 < p_T^{\text{assoc}} < 2.5$ (top) and $2.5 < p_T^{\text{assoc}} < 3 \text{ GeV/c}$ (bottom).

Appendix G (Continued)

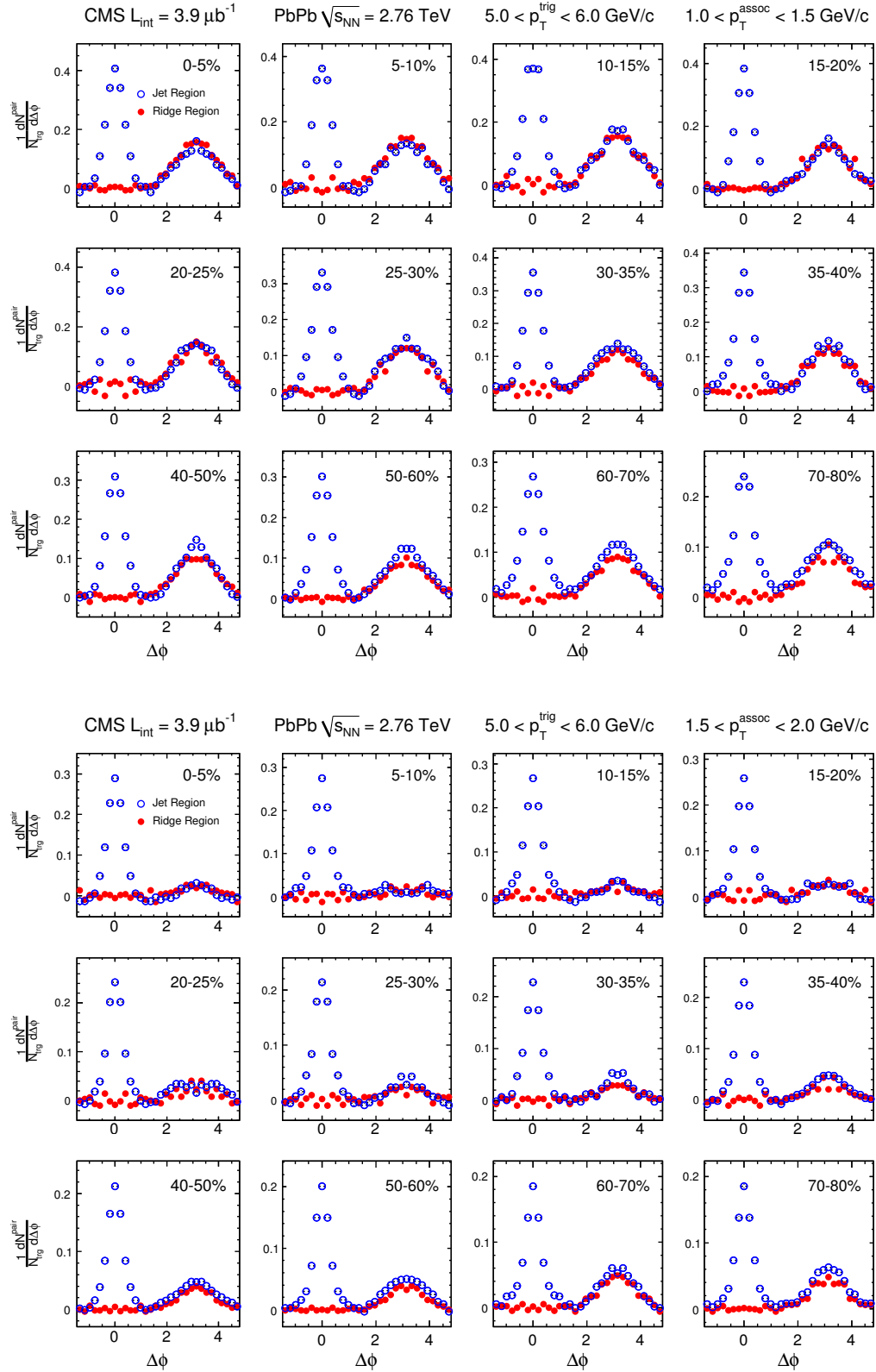


Figure 91. Flow-subtracted one-dimensional $\Delta\phi$ projections for jet and ridge region $5 < p_T^{\text{trig}} < 6$ GeV/c with $1 < p_T^{\text{assoc}} < 1.5$ (top) and $1.5 < p_T^{\text{assoc}} < 2$ GeV/c (bottom).

Appendix G (Continued)

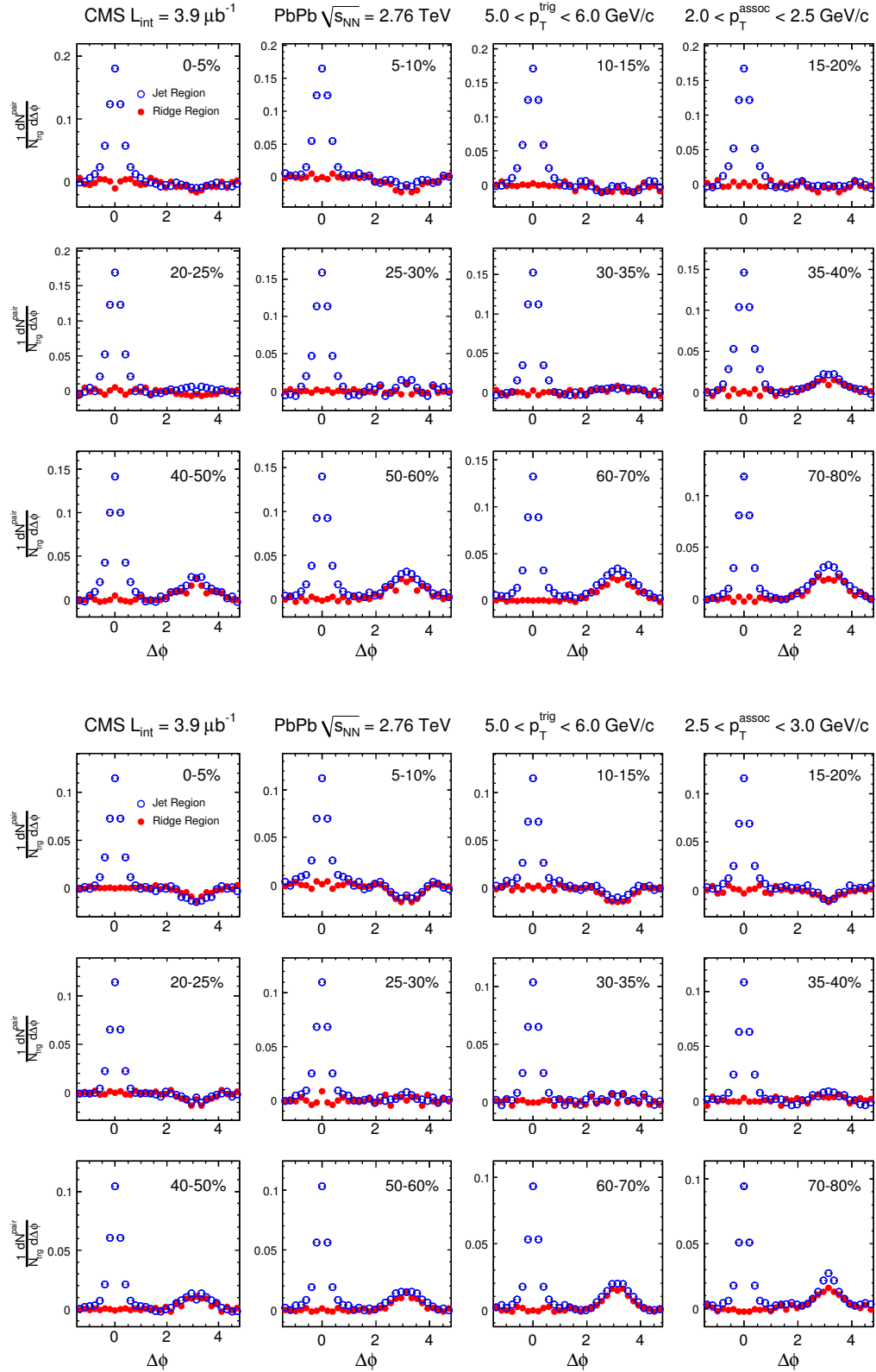


Figure 92. Flow-subtracted one-dimensional $\Delta\phi$ projections for jet and ridge region $5 < p_T^{\text{trig}} < 6$ GeV/c with $2 < p_T^{\text{assoc}} < 2.5$ (top) and $2.5 < p_T^{\text{assoc}} < 3$ GeV/c (bottom).

Appendix G (Continued)

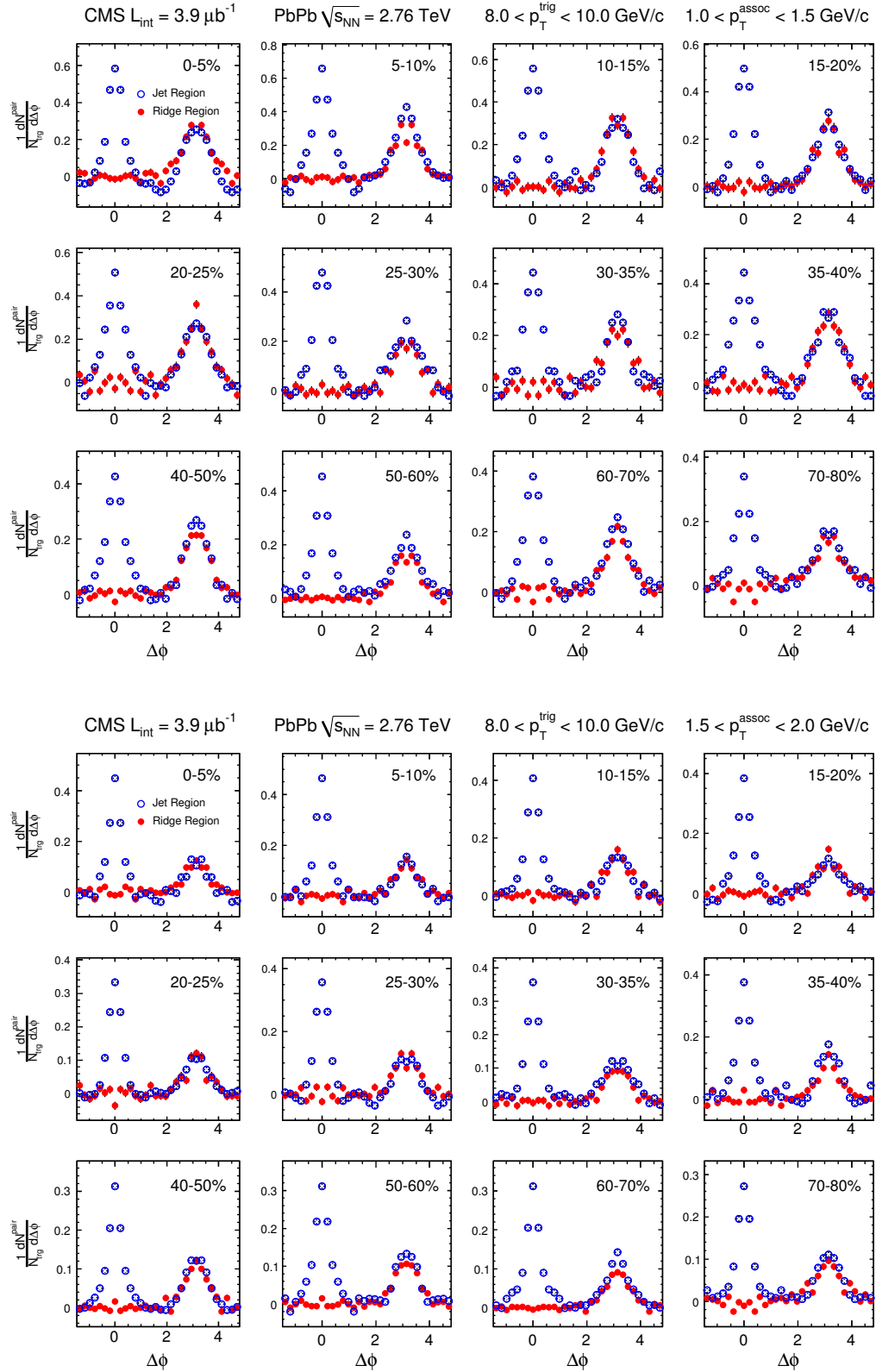


Figure 93. Flow-subtracted one-dimensional $\Delta\phi$ projections for jet and ridge region $8 < p_T^{\text{trig}} < 10$ GeV/c with $1 < p_T^{\text{assoc}} < 1.5$ (top) and $1.5 < p_T^{\text{assoc}} < 2$ GeV/c (bottom).

Appendix G (Continued)

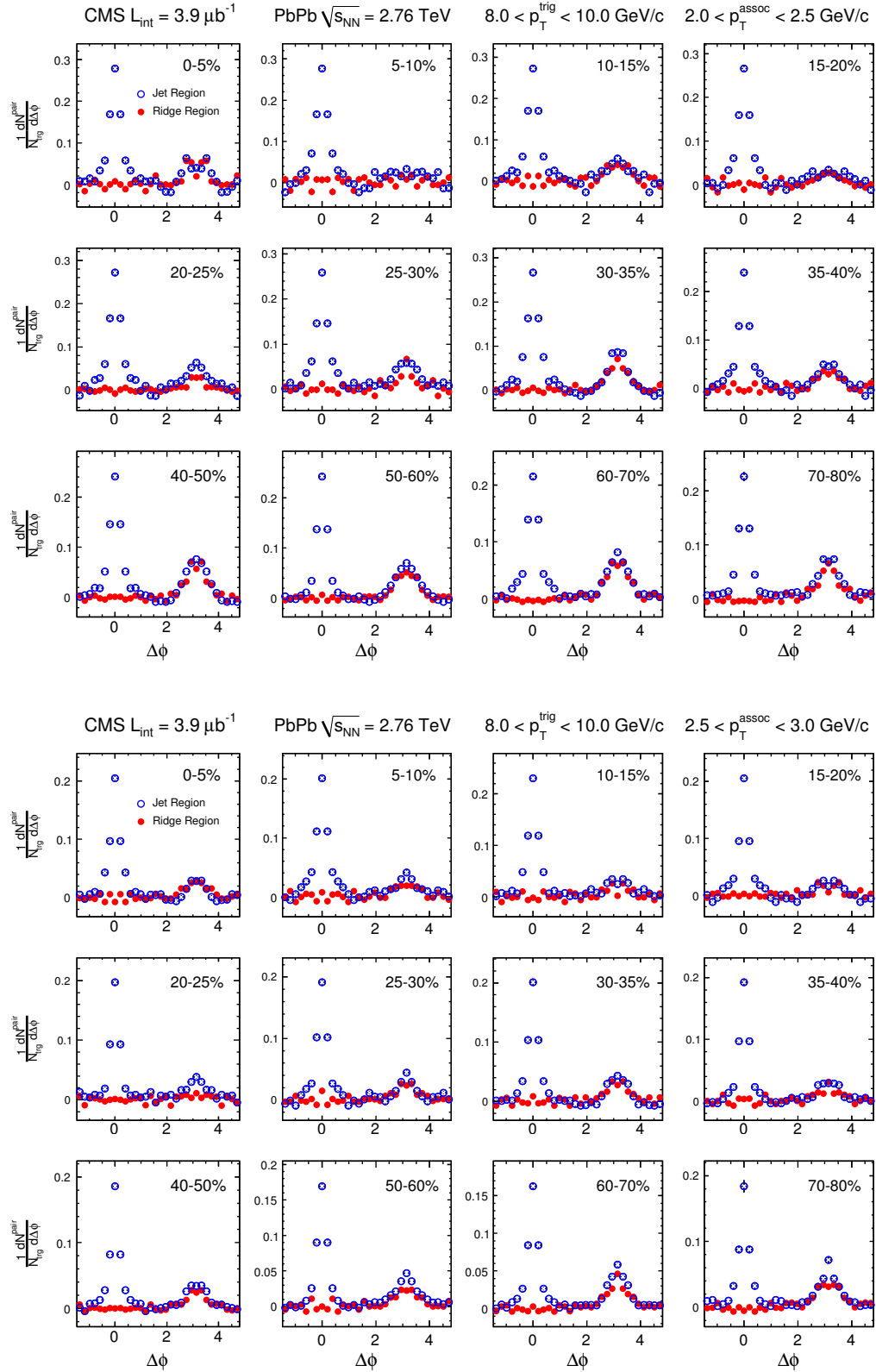


Figure 94. Flow-subtracted one-dimensional $\Delta\phi$ projections for jet and ridge region $8 < p_T^{\text{trig}} < 10$ GeV/c with $2 < p_T^{\text{assoc}} < 2.5$ (top) and $2.5 < p_T^{\text{assoc}} < 3$ GeV/c (bottom).

Appendix H

FLOW SUBTRACTED AWAY-SIDE JET-REGION YIELDS

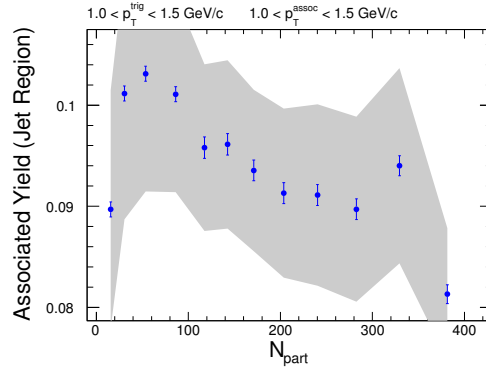


Figure 95. Away-side flow-subtracted jet-region yields for $1 < p_T^{\text{trig}} < 1.5 \text{ GeV/c}$ and $1 < p_T^{\text{assoc}} < 1.5 \text{ GeV/c}$.

Appendix H (Continued)

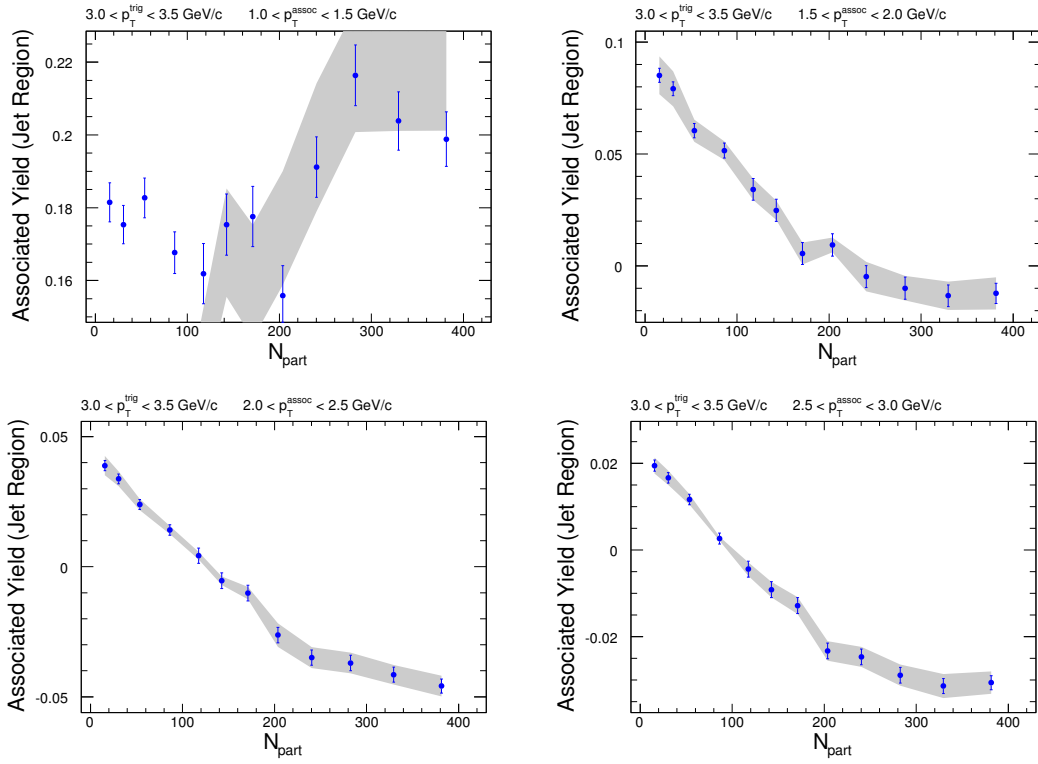


Figure 96. Away-side flow-subtracted jet-region yields for $3 < p_T^{\text{trig}} < 3.5 \text{ GeV/c}$ and $1 < p_T^{\text{assoc}} < 1.5 \text{ GeV/c}$ (upper left), $1.5 < p_T^{\text{assoc}} < 2 \text{ GeV/c}$ (upper right), $2 < p_T^{\text{assoc}} < 2.5 \text{ GeV/c}$ (lower left), $2.5 < p_T^{\text{assoc}} < 3.0 \text{ GeV/c}$ (lower right).

Appendix H (Continued)

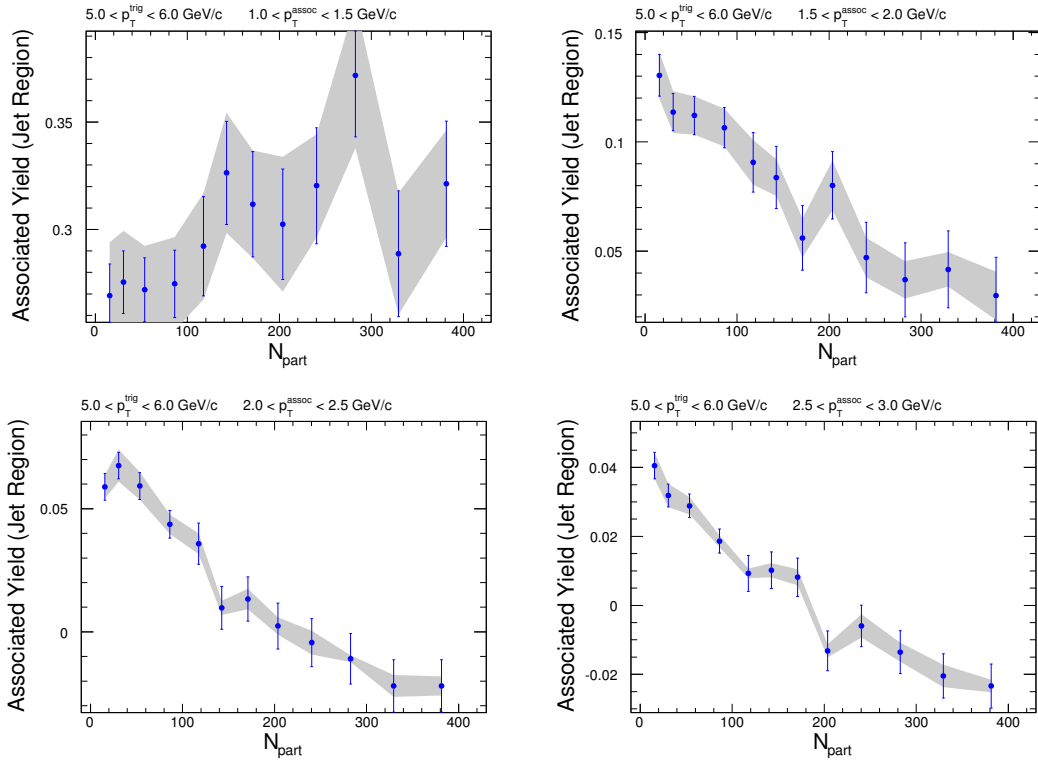


Figure 97. Away-side flow-subtracted jet-region yields for $5 < p_T^{\text{trig}} < 6 \text{ GeV/c}$ and $1 < p_T^{\text{assoc}} < 1.5 \text{ GeV/c}$ (upper left), $1.5 < p_T^{\text{assoc}} < 2 \text{ GeV/c}$ (upper right), $2 < p_T^{\text{assoc}} < 2.5 \text{ GeV/c}$ (lower left), $2.5 < p_T^{\text{assoc}} < 3.5 \text{ GeV/c}$ (lower right).

Appendix H (Continued)

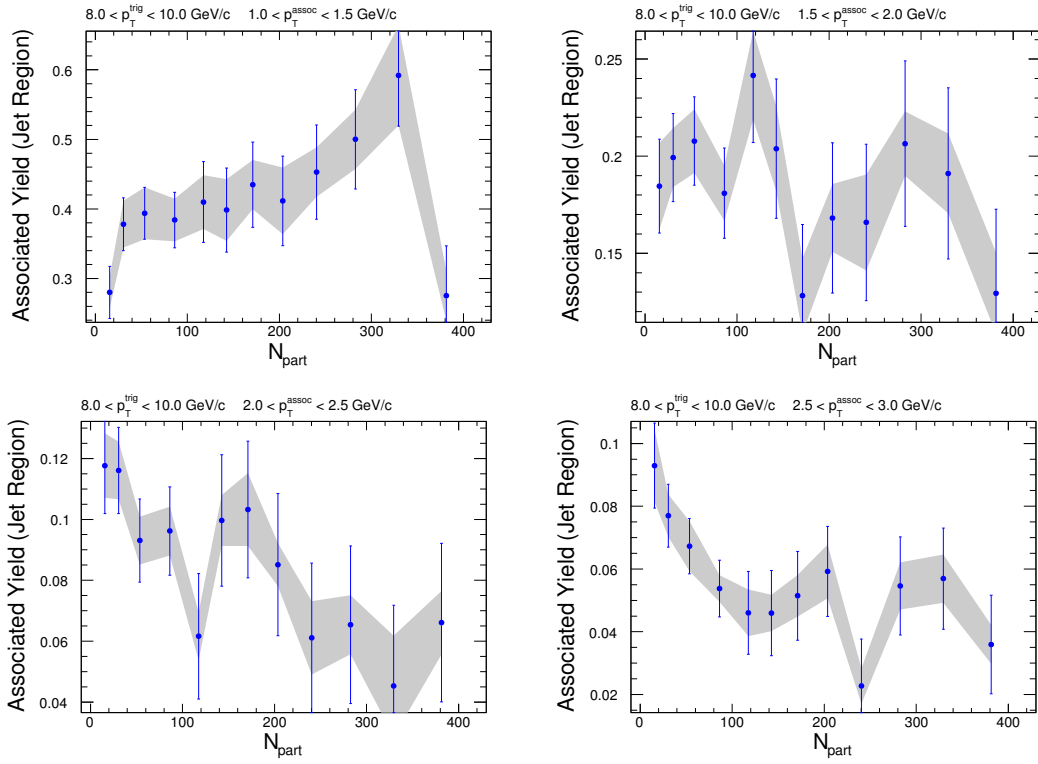


Figure 98. Away-side flow-subtracted jet-region yields for $8 < p_T^{\text{trig}} < 10 \text{ GeV/c}$ and $1 < p_T^{\text{assoc}} < 1.5 \text{ GeV/c}$ (upper left), $1.5 < p_T^{\text{assoc}} < 2 \text{ GeV/c}$ (upper right), $2 < p_T^{\text{assoc}} < 2.5 \text{ GeV/c}$ (lower left), $2.5 < p_T^{\text{assoc}} < 3.0 \text{ GeV/c}$ (lower right).

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