JOINT INSTITUTE FOR NUCLEAR RESEARCH

Veksler and Baldin laboratory of High Energy Physics

FINAL REPORT ON THE SUMMER STUDENT PROGRAM

Measurement of the angular coefficients in Z-boson events using muon pairs on generator level at $\sqrt{s}$ = 13 TeV with the CMS Detector

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Introduction

The Drell-Yan production is extremely important process in High Energy Physics , the lepton pairs production mechanism allows us to verify the Standard Model of elementary particles, moreover to search for new physics signals beyond the Standard Model.

Experiments reveal that the angular distribution of leptons produced in Drell-Yan process is no azimuthally symmetric, when the dilepton's transverse momentum is becoming larger. The reason for that is QCD effects, which involve emission of partons of large transverse momenta. Previous investigations with earliest data, when dileptons had low transverse momenta [1,2], demonstrated a good agreement with theory for Drell-Yan production [3].

For Drell-Yan process a general expression for the lepton angular distribution is written:

$$\frac{d\sigma}{d\Omega} \propto 1 + \lambda cos^2\theta + \mu sin2\theta cos\phi + \frac{\nu}{2} sin^2\theta cos2\phi, \tag{1}$$

where θ and φ refer to the polar and azimuthal angels of l^-(e^-or $\mu-$) in the rest frame of γ^*. The azimuthal dependencies of the lepton angular distributions are described by the parameters μ and ν. There is Lam-Tung relation, which is given by

$1 - \lambda = 2\nu$, was found to be violated in pion-induced Drell-Yan experiments. The measurement of lepton angular distributions in gauge boson productions, was considered as a powerful tool for comprehending the productions mechanism of mentioned bosons [4, 5].

The CMS and ATLAS Collaborations at the LHC reported results of the lepton angular distribution of γ^*/Z production in pp collision at $\sqrt{s} = 8$ TeV that λ,μ and ν strongly depend on p_T .

Chapter 1

Drell-Yan process

1.1 Proton-proton Collisions

Partons are constituents of protons. The subcomponents are presented by 3 valence quarks (uud) embedded in a sea of quark anti-quark pairs(namely sea quarks) and gluons. The number of partons in the proton depends on a physical scale probed by the momentum transfer Q^2 of the scattering process. In accordance with the scale, partons number soars with larger momentum transfer. The probability density of a parton i in the proton is defined as $f_i(x, Q^2)$, depending on the scale of the process Q^2 and the parton momentum fraction x with respect to the proton momentum. These functions are called parton density functions(PDF) and can be extracted from fits to experimental data. The PDFs are universal and thus do not depend on the production process and can therefore be determined for different values of Q^2.

At high energies, the partons are assumed to be quasi free due to the principle of asymptotic freedom and the interaction between them can be neglected. In an high energy proton-proton collision, the hard scattering process (hard means large momentum transfer Q^2 is initiated by two partons of the two protons. Figure 1.2 shows an illustration of the production of a Z^0/γ^* resonance. The square centre-of-mass energy of the proton-proton collision is defined as

$$s = (P_1 + P_2)^2, \tag{1.1}$$

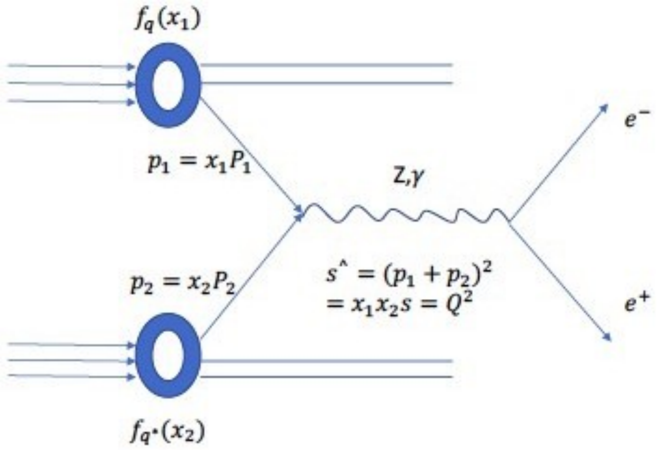


Figure 1.1: This image reveals a pp collision in the parton model. The four- momenta of the protons are defined as $P_{1,2}$, giving the four-momenta of the partons initiating the hard scattering with $p_{1,2}$, depending on the momentum fractions $x_{1,2}$. The interaction of the quark and anti-quark produces a Z^0/γ^*resonance decaying into two leptons l^+l^- in our case $\mu^+\mu^-$.

where P_i is the four-momentum of proton i. In the collinear approximation, which means neglecting the transverse momentum of the partons, the four-momenta of the two partons can be written as

$$p_1 = \frac{(s)^{1/2}}{2}(x_1, 0, 0, x_1), \tag{1.2}$$

$$p_1 = \frac{(s)^{1/2}}{2}(x_2, 0, 0, -x_2), \tag{1.3}$$

with the momentum fraction x_i of parton i. The square centre-of-mass energy of the parton scattering yields

$$s = (p_1 + p_2)^2 = x_1 x_2 s = Q^2. \tag{1.4}$$

In order to calculate the cross section of a QCD process, the collinear factorisation theorem can be used. The factorization theorem separates the short-distance terms like the partonic cross section including QCD radiation, which can be computed perturbatively, and long-distance contributions, such as hadronization, PDF, and multiple soft interactions. The long-distance contributions can not be computed precisely in pQCD and are described by phenomenological models. The cross section of a pp collision can then be written as a convolution of the partonic hard cross section and the PDFs of the incoming partons. In the perturbative expansion of the partonic cross section at next-to-leading order (NLO) (or higher orders), the real and virtual parton emissions have to be included. Due to collinear and soft emissions in the perturbative expansion of the cross section, the perturbative series breaks down. In order to cancel the divergent behaviour at small scales the factorisation scale μ_F is introduced. The collinear singularities can be absorbed in the PDFs by introducing renormalised scale-dependent PDFs $f_i(x, \mu_F)$.

The rapidity y of the Drell-Yan lepton pair is defined as

$$y = \frac{1}{2}(\frac{E + p_z}{E - p_z}) = \frac{1}{2}ln(\frac{x_1}{x_2}). \tag{1.5}$$

The rapidity can be written in terms of the momentum fraction x_1 and x_2. The kinematic relation of the rapidity and the momentum fraction x yields

$$x_1 = M/(s)^{1/2} exp(y), x_2 = M/(s)^{1/2} exp(-y). \tag{1.6}$$

The kinematic region of QCD, where the hard scale of the process is large compared to the QCD scale and small compared to the total centre-of-mass energy, i.e.

$$A_{QCD} << \mu << (s)^{1/2}, \tag{1.7}$$

is defined as the small-x region. In this corner of phase, different physics effects are not completely understood, e.g. the strong increase of the PDFs or parton saturation. The phenomenology of small-x QCD can be studied by measuring asymmetric hard QCD collisions. In this configuration one parton has a large value in x and the other a small value in x, which leads to activity in the forward region(large rapidity values y) of the detector.

1.2 Drell-Yan Production

The Drell-Yan process was first presented by Drell and Yan [3] describing quark anti-quark annihilation into a lepton pair l^+l^- with invariant mass $M^2 = (p_{l_+} + p_{l_-})^2$ 1 GeV^2. In hadron-hadron collisions, the quark and anti-quark are constituents of the two incoming hadrons and can create an off-shell virtual boson (Z or γ), which then directly decays into two leptons. In the following, the Drell-Yan cross section is calculated first in the parton model and including perturbative corrections, following the calculations in [6]. The figures below illustrates this DY process in different ways.

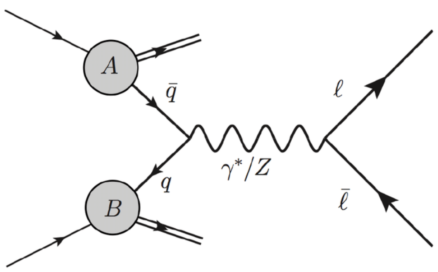


Figure 1.2: Drell-Yan process

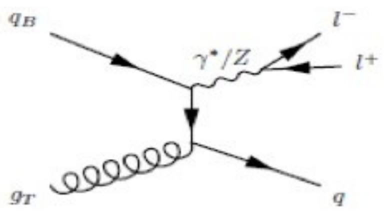


Figure 1.3: Drell-Yan process(a)

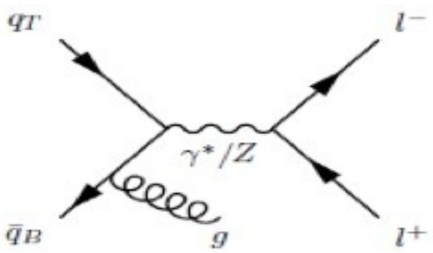


Figure 1.4: Drell-Yan process(b)

Collision Kinematics

The transverse momentum is defined as

$$p_t = (p_x^2 + p_y^2)^{\frac{1}{2}} \tag{1.8}$$

and represents the component of the particle momentum transverse to the beamline. Rapidity is defined as

$$y = \frac{1}{2} ln \frac{E+p_z}{E-p_z}$$

Here, E is the energy of the particle and p_z is its momentum along the proton beamline. Rapidity is generally used to present the angular distribution of particles. The shape of the rapidity distributin is ivariant under a relativistic boost along the z axis, so y is a better choise of a variable than the polar angle θ

Pseudorapidity is approximately equal to the rapidity in the limit where a particle's momentum is much greater than its mass. Pseudorapidity is defined as:

$$\eta = -\ln \tan\left(\frac{\theta}{2}\right) \tag{1.10}$$

The invariant mass of two particles is defined as:

$$m^2 = (P_1 + P_2)_\mu (P_1 + P_2)^\mu \tag{1.11}$$

Chapter 2

Angular Coefficients

The lepton angular distribution in the γ^*/Z rest frame is expressed by both the CMS and ATLAS Collaboration as [7]

$$\frac{d\sigma}{d\Omega} \propto (1 + cos^2\theta) + \frac{A_0}{2}(1 - 3cos^2\theta) + A_1 sin2\theta cos\phi + \frac{A_2}{2} sin^2\theta cos2\phi +$$

$$+ \mathbf{A_3} sin\theta cos\phi + A_4 cos\theta + A_5 sin^2\theta sin2\phi + A_6 sin2\theta sin\phi + A_7 sin\theta sin\phi, \quad (2.1)$$

where θ and φ are the polar and azimuthal angles of l^-(e^-or $\mu-$) in the rest frame of γ^*/Z. In this paper Collins-Soper (CS) frame is used to measure the angular coefficients A_i, considering the momentum of the beam proton closest in rapidity to the Z boson as the "target momentum". In the second formula, the parameters A_0, A_1 and A_2 are related to the polarization of the Z boson, whilst A_3 and A_4 are also sensitive to the V-A structure of the couplings of the muons. All angular coefficients vanish as the Z boson transverse momentum q_T approaches zero except for A_4, which is the electroweak parity violation term.

The relation $A_0 = A_2$ is known as the Lam-Tung relation, it reflects the full transverse polarization of vector boson couplings to quarks, as well as rotational invariance. Processes containing non-planar configuration, as an example higher order multi-gluon emission smear the transverse polarization, leading to $A_2 < A_0$.

In pp and $p\bar{p}$ collisions angular coefficients are different. For $p\bar{p}$ collisions, the Z boson production occurs mainly through the $q\bar{q}$ channel, whereas the contribution of of the qg Compton process is larger in pp collisions than $p\bar{p}$collisions.

The CMS Collaborations at the LHC reported high-statistics measurements of the lepton angular distribution of γ^*/Z production in pp collision at $\sqrt{s}$ = 8 TeV[8]. A violation of the Lam-Tung relation was found for these data at large p_T.

The angular coefficients are measured in bins of p_T and $|y|$, by fitting the 2D ($cos\theta, \varphi$) distribution.

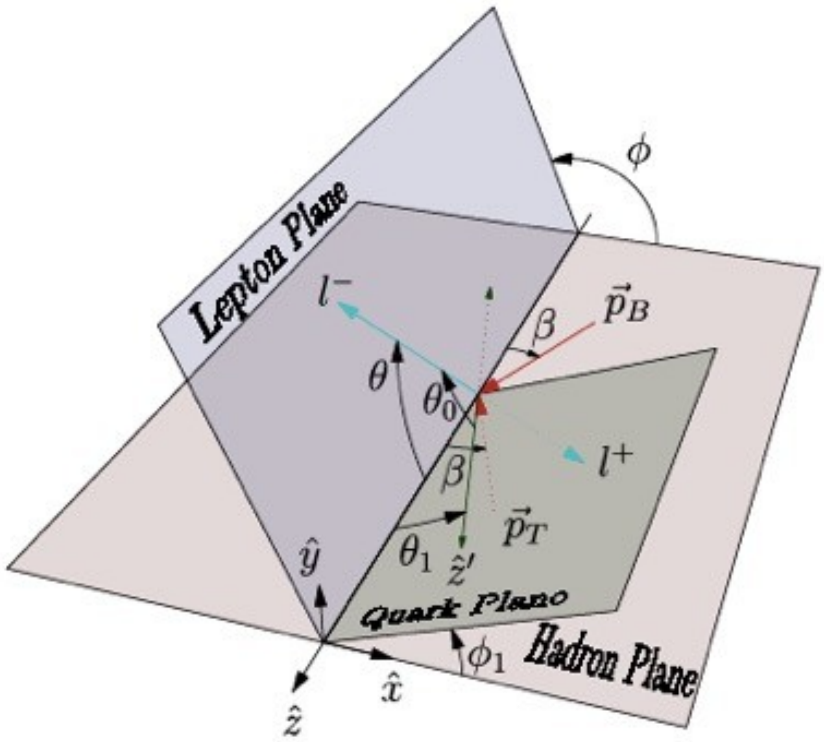


Figure 2.1: Collins-Soper Frame [7]

Figure 2.1 illustrates the Collins-Soper frame and different angles and planes in the rest frame of γ/Z. The hadrom plane is formed by two hadron momentum vectors P_B(B-beam) and P_T (T-target). The l^- and l^+ are emitted back-to-back with equal momenta in the rest frame of γ/Z.

In the γ/Z rest frame, a pair of collinear q and q^- with equal momenta annihilate into a γ/Z. The momentum unit vector of q is defined as z`, and the quark plane is formed by the $z$` and z axes. The polar and and azimuthal angles of the z` axis in the Collins-Soper frame are denoted as θ_1 and φ_1.

2.1 Selection of working points

The values for each angular coefficient could be obtained after fitting 2D histograms ($cos\theta, \varphi$) in bins of rapidity, invariant mass and transverse momentum. Figures below were built for $0.9<y<1.35$, $80<M<100$ GeV and $0<p_T<600$ GeV.

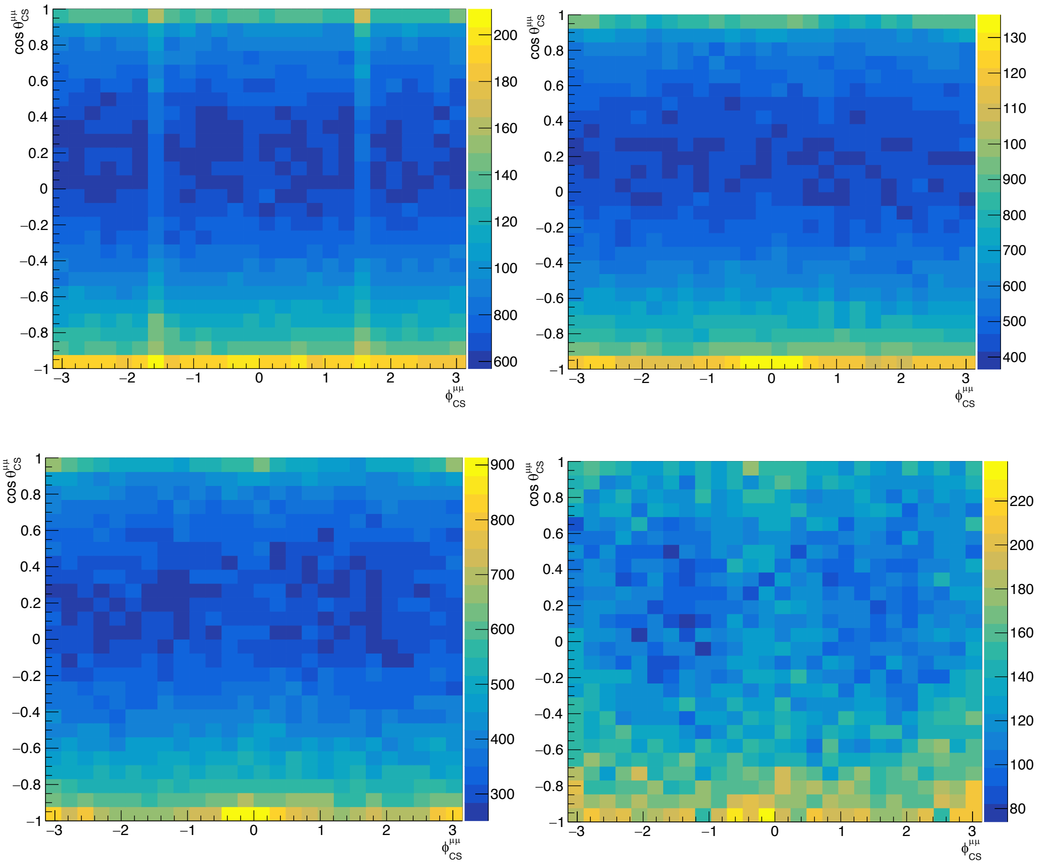


Figure 2.1.1.: 2D histograms $0.9<y<1.35$, $80<M<100$ GeV and $0<p_T<600$ GeV.

To check the rapidity dependence we built also for 1.35<*y<2.4 case.*

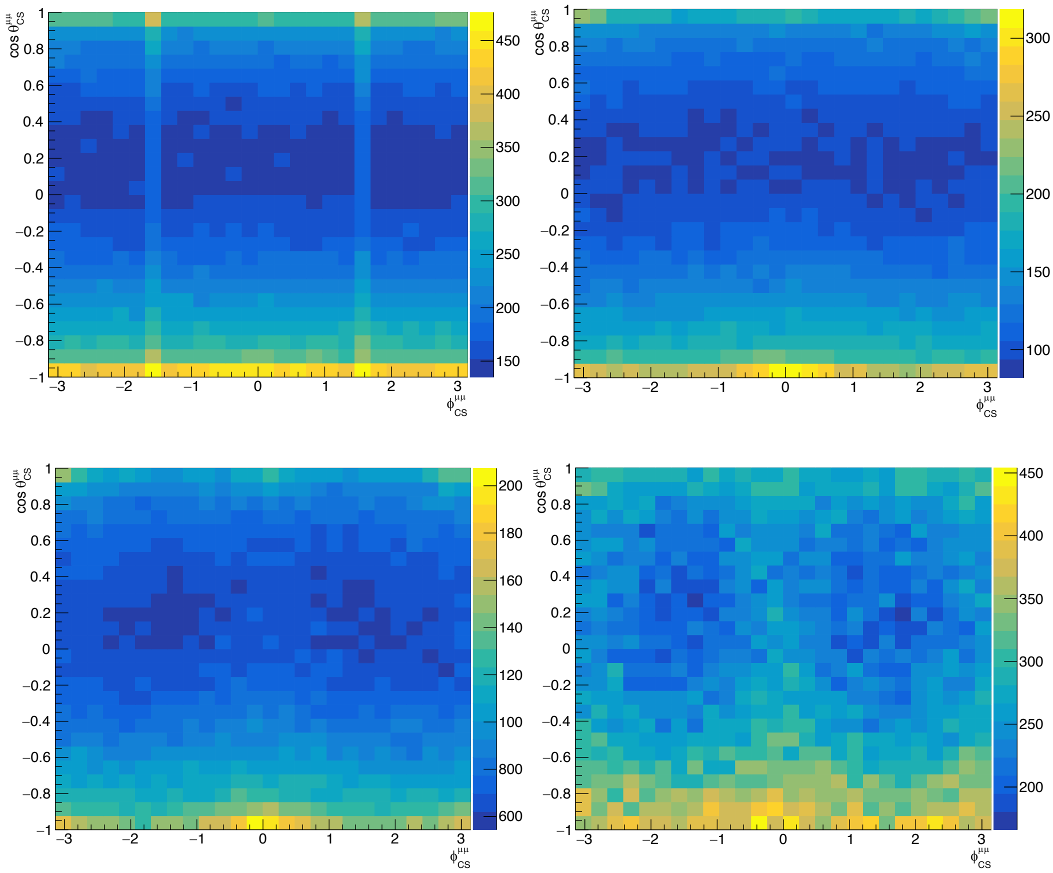
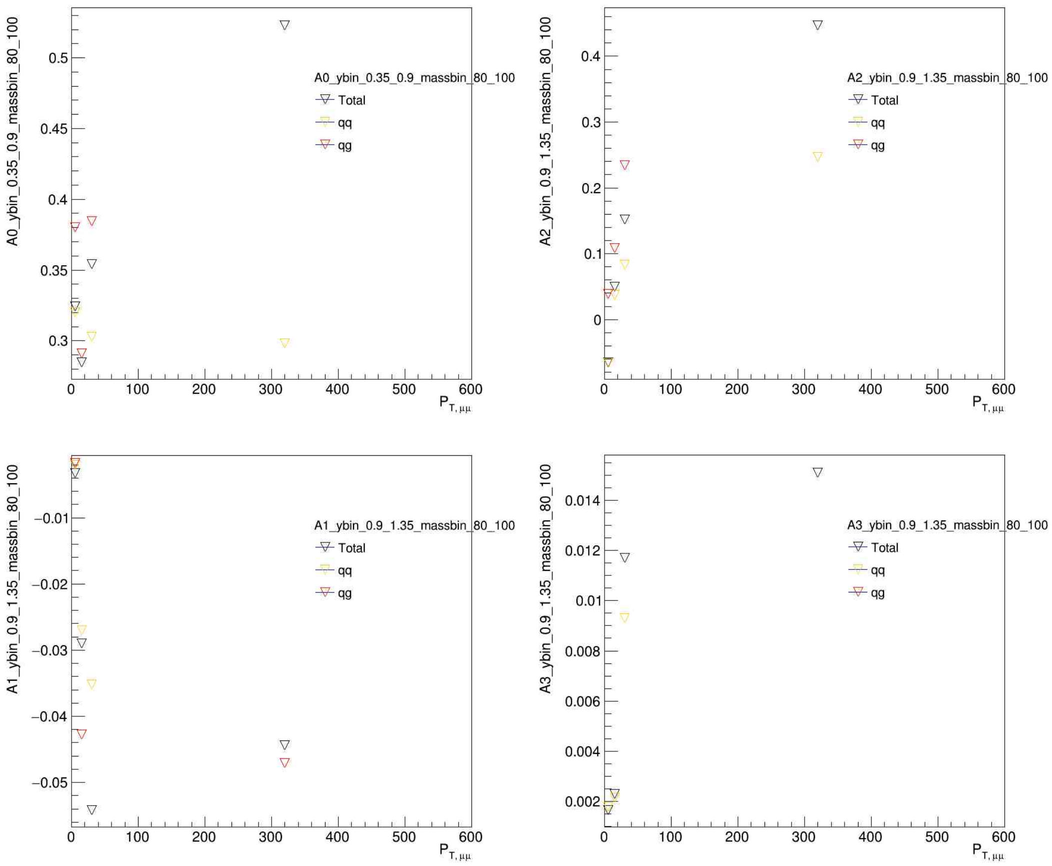


Figure 2.1.2.: 2D histograms 1.35<*y<2.4, 80<M<100 GeV* and 0<p_T<600 *GeV*.

2.2 Angular Coefficients as function of transverse momentum

Figure 2.2 shows the angular distribution coefficients at mid rapidity region between 0.9 and 1.35 measured on the generator. We can easily observe some salient features in the transverse momentum dependencies of A.



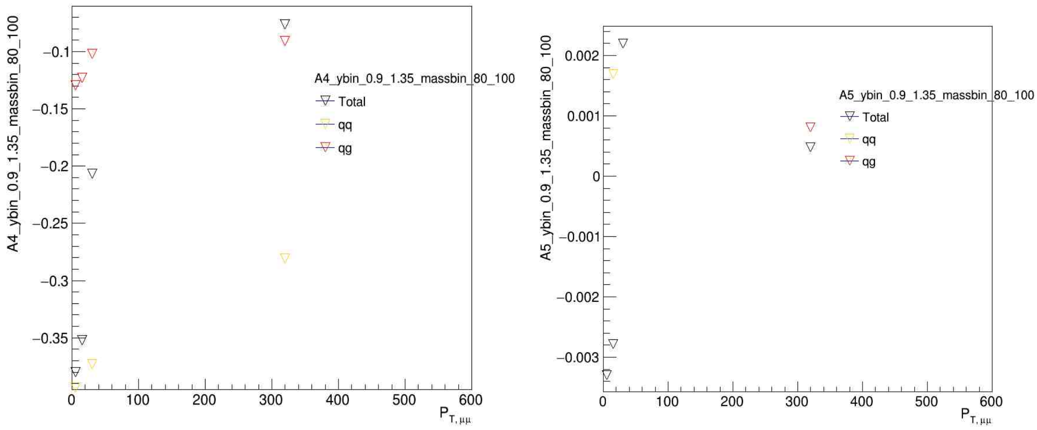
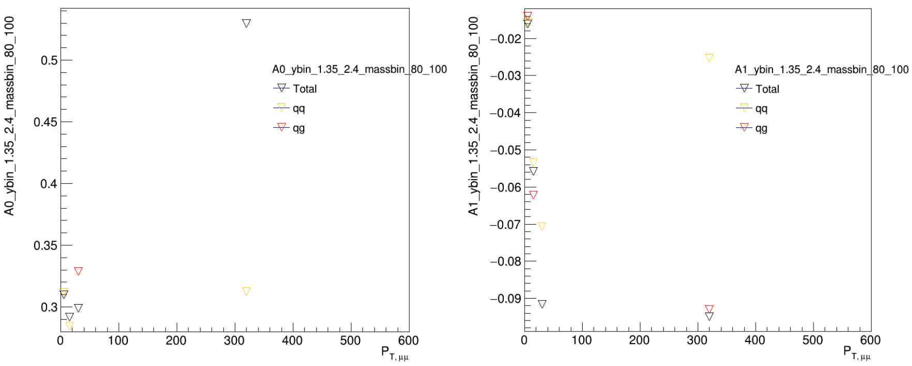


Figure 2.2: Angular coefficients distribution versus transverse momentum.

Figures reveal that A_{0-3} are in the vicinity of zero, if p_T tends to smallest values. However, A_4 shows that it is non-zero, even if p_T is zero. The relation A_0=A_2 is violated, as there is no similar trends.

As p_T ->0, show that A_{0-3} all approach zero, since θ tends to zero.

While looking at the graphs below, which was performed in the rapidity region 1.35 <y<2.4, one can say that there is strong dependence on y, as distributions differ from that in Figure 2.2.



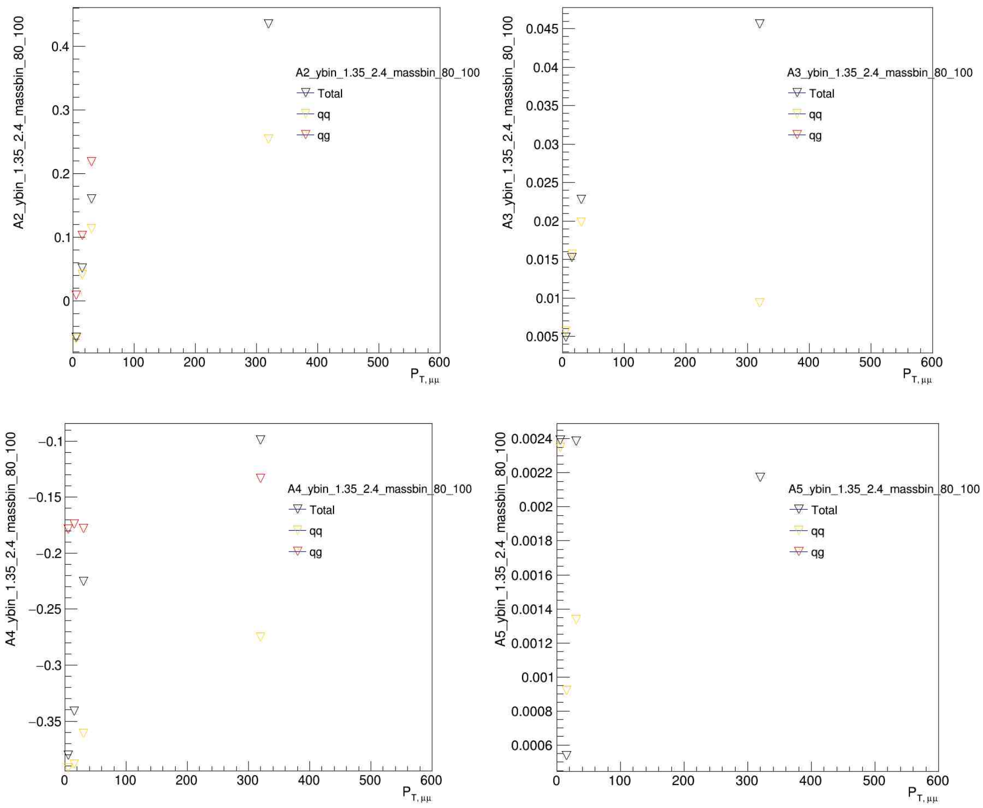
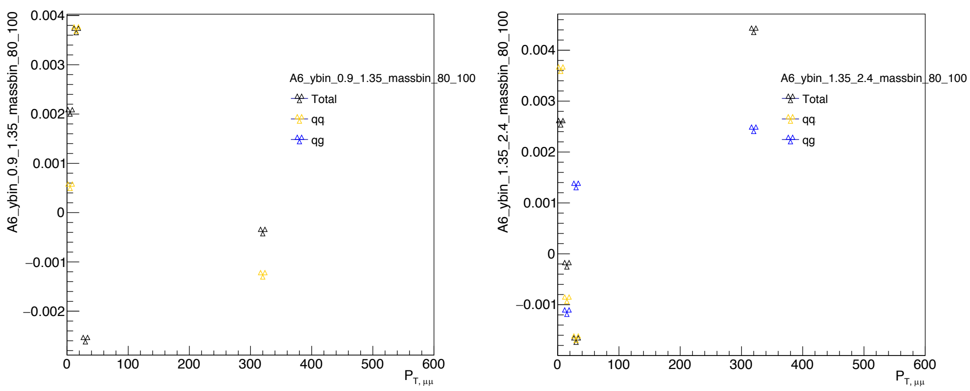


Figure 2.3: Strong rapidity dependence of angular coeffcients.

In Figure 2.4 : We tried to show that coefficients A_6, A_7 are very small and considered to be zero.



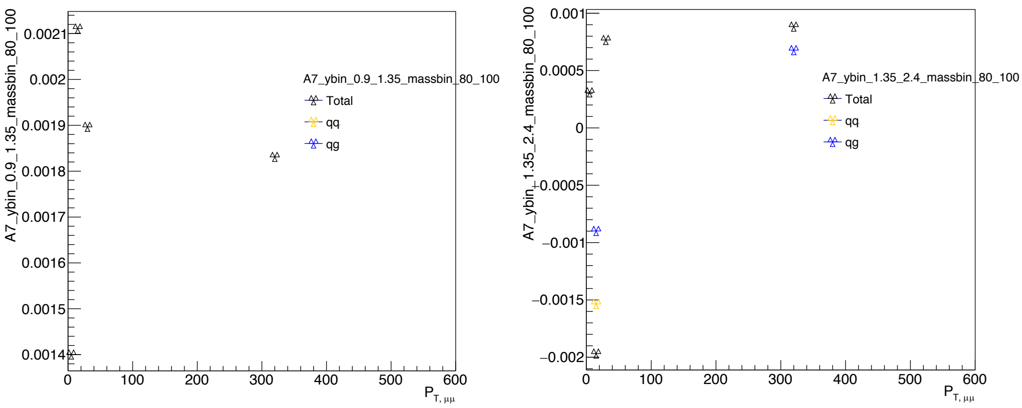


Figure 2.4: Strong rapidity dependence of angular coeffcients.

Chapter 3

Conclusion

The angular coefficients are very important to understand the Z boson production mechanism. In this paper we tried to explain how these coefficients are obtained and we provided interpretation for them. The distributions for the coefficients were obtained on the generator level (Monte Carlo simulation) on CMS Experiment.

As it was mentioned above, these coefficients depend on several parameters, namely transverse momentum p_T, rapidity y and invariant mass M, therefore we selected different values of p_T, y and M. This paper shows $A_i = A_i(p_T)$ for the case of $0.9<y<1.35$, $80<M<100$ GeV; $0<p_T<600$ GeV and $1.35<y<2.4$, $80<M<100$ GeV; $0<p_T<600$ GeV.

We show that different angular coefficients are governed by 2 parameters: azimuthal and polar angles. The inequality relation between $A_0$and A_2, relevant for the violation of the Lam-Tung relation, due to the noncomplanarity between the hadron and quark planes was observed. The strong rapidity dependence was observed too. These coefficients were measured for QG and QQ^* production mechanisms too.

In conclusion, the major angular coefficients are presented, for the production of the Z boson decaying to lepton pairs (muon pairs) as a function of transverse momentum and rapidity in pp collisions. These results are very critical for the future measurements, for instance the measurement of the Z boson mass.

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