Active Role of Gluons in Hadron Interactions

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Abstract

Multiparticle hadron production in e^+e^- annihilation provides a sensitive probe of the underlying dynamics of Quantum Chromodynamics, particularly the evolution of quark–gluon cascades and their transition into observable hadrons. In this work, the active role of gluons in particle production is investigated within the framework of the Gluon Dominance Model, where the process is described as a two-stage mechanism consisting of a stochastic partonic cascade followed by hadronization. The cascade is treated as a Markov branching process governed by elementary QCD transitions—gluon fission, quark bremsstrahlung, and quark–antiquark pair production—and is characterized by an evolution parameter that controls the development of the jet. The statistical properties of the cascade are formulated through the generating function $Q(z) = \sum_{n=0}^{\infty} P_n z^n$, which provides a complete description of multiplicity distributions and enables the determination of observables such as the average multiplicity and correlation moments, including correlation observables as measures of particle correlations. The theoretical formulation is implemented within the CERN ROOT framework, where model parameters are extracted through χ^2 minimization using the MINUIT algorithm by fitting calculated multiplicity distributions to experimental data at different center-of-mass energies. The results demonstrate that gluon-driven processes dominate particle production, while the behavior of multiplicity distributions and correlation observables indicates that at lower energies the quark–gluon cascade remains weakly developed and hadronization effects are predominant, with a transition toward a more developed cascade regime at higher energies. The observed deviation from Poisson statistics and consistency with broader distributions such as the negative binomial form further confirm the presence of correlated particle production arising from branching dynamics. These results establish a direct connection between QCD cascade evolution and experimentally observed multiplicity patterns, highlighting the central role of gluons in hadron production.

1. Introduction

The study of Multiparticle hadron production in e^+e^- annihilation provides a clean environment for investigating the dynamics of quark–gluon cascades, owing to the absence of initial-state hadronic structure. While Quantum Chromodynamics (QCD) provides a well-established framework for describing the interactions of quarks and gluons at short distances, the mechanism by which these partons evolve into complex multiparticle final states remains only partially understood. This difficulty arises from the interplay between perturbative dynamics, governing the early stages of parton evolution, and non-perturbative processes responsible for hadron formation. Consequently, statistical observables such as multiplicity distributions and their moments serve as essential probes of the underlying dynamics.

An instructive analogy can be drawn from Quantum Electrodynamics (QED), where electromagnetic cascades develop through successive processes such as bremsstrahlung and electron–positron pair production, leading to a multiplicative increase in particle number. A similar cascade picture arises in QCD through successive parton branching. However, due to the non-Abelian nature of QCD, gluons carry color charge and undergo self-interaction, resulting in gluon multiplication via processes such as gluon splitting. This leads to a significantly richer cascade structure than in QED and plays a central role in determining the multiplicity and correlation properties of produced particles.

The theoretical description of such cascades has been formulated within the framework of stochastic branching processes. In particular, the treatment of QCD jets as Markov branching processes introduced by *Giovannini* [1] provides a consistent probabilistic description of quark–gluon evolution. In this approach, the cascade is governed by elementary QCD branching processes, as formulated within the probabilistic framework of jet evolution. This formulation naturally leads to a statistical description of particle production through generating functions, which encode multiplicity distributions and their associated moments.

Early theoretical descriptions of multiparticle production were also developed within the framework of dual models and scaling approaches, notably in the work of *Konishi, Ukawa, and Veneziano* [3], where multiplicity distributions and their scaling properties were investigated in the context of strong interactions. These studies provided important insights into the statistical nature of particle production and laid the groundwork for later developments based on QCD branching dynamics.

In the case of e^+e^- annihilation, the absence of initial-state hadronic structure provides a comparatively clean environment for studying quark–gluon cascade dynamics, allowing a more direct connection between theoretical models and experimental observations.

Experimental studies have shown that multiplicity distributions deviate significantly from simple Poisson expectations, indicating the presence of correlations among produced particles. Various statistical models have been proposed to describe these features, including branching-based distributions such as the Furry–Yule form and the negative binomial distribution, which successfully describes experimental data over a wide range of energies [2]. In addition, the concept of Koba–Nielsen–Olesen (KNO) scaling suggests that multiplicity distributions exhibit approximate self-similarity when expressed in terms of scaled variables, reflecting the underlying cascade dynamics.

Despite these developments, a complete description of multiparticle production must account for the transition from partonic cascades to hadronic final states. Since hadronization occurs in the non-perturbative regime of QCD, it cannot be derived from first principles and must be modeled phenomenologically. The Gluon Dominance Model provides such a framework, in which gluons, due to their self-interacting nature and larger color factor, are expected to play a dominant role in particle production. This approach offers a natural explanation for the observed features of multiplicity distributions and their evolution with energy.

The present work builds upon these developments by investigating multiparticle hadron production in e^+e^- annihilation within the framework of the Gluon Dominance Model. The analysis combines the probabilistic description of quark–gluon cascades with a statistical treatment of hadronization and is implemented within the CERN ROOT framework, where model parameters are extracted using χ^2 minimization based on the MINUIT algorithm through fits to experimental multiplicity distributions at different center-of-mass energies. This enables a detailed study of the energy dependence of multiplicity distributions, correlation moments, and cascade behavior, with particular emphasis on the role of gluons in shaping the multiplicity structure.

Through this approach, the work aims to provide a coherent and quantitatively consistent description of multiparticle production, linking QCD-based cascade dynamics with experimentally observed statistical properties and offering insight into the evolution of quark–gluon systems with increasing energy.

2. Multiparticle Production Dynamics in QCD Jets

The theoretical description of Multiparticle production in e^+e^- annihilation can be described in terms of the evolution of quark and gluon jets within Quantum Chromodynamics. In this framework, particle production arises from a cascade of successive branching processes, in which an initial high-energy parton undergoes repeated splittings, leading to a multiplicative growth of secondary partons. The stochastic nature of this evolution allows the cascade to be described as a Markov branching process, as developed in the work of *Giovannini* [1], establishing a direct connection between QCD dynamics and the statistical properties of the observed final state.

In the case of e^+e^- annihilation, the initial state consists of a quark–antiquark pair produced from the electroweak interaction, which subsequently develops into hadronic jets through QCD cascade processes.

The development of the parton cascade is characterized by an evolution parameter Y, which effectively measures the "thickness" of the jet and governs the number of branching steps. It is defined as

$$Y = \frac{1}{2\pi b}\log\left[1+\alpha b\log\frac{Q^2}{\mu^2}\right]$$

where Q^2 is the virtuality scale, μ^2 is a reference scale, and b depends on the number of colors and active quark flavors. As Y increases with energy, the cascade becomes more developed, allowing for a larger number of branching processes.

The evolution of the cascade is governed by three elementary QCD transitions: gluon fission $g \to g + g$, quark bremsstrahlung $q \to q + g$, and gluon conversion into quark–antiquark pairs $g \to q + \bar{q}$. These processes define the probabilistic structure of the cascade and are assumed to occur independently in an infinitesimal interval ΔY, consistent with the Markovian nature of the evolution.

The probabilistic nature of the cascade naturally leads to a statistical description of particle production, in which generating functions provide a compact representation of multiplicity distributions. For gluon-initiated and quark-initiated jets, the generating functions are defined as

$$G(u_g, u_q; Y) = \sum_{n_g, n_q = 0}^{\infty} P_{1,0;n_g,n_q}(Y) u_g^{n_g}, u_q^{n_q}$$

$$Q(u_g, u_q; Y) = \sum_{n_g, n_q = 0}^{\infty} P_{0,1;n_g,n_q}(Y) u_g^{n_g}, u_q^{n_q}$$

where $P_{m_g,m_q;n_g,n_q}(Y)$ denotes the probability that an initial system containing m_g gluons and m_q quarks evolves into a state with n_g gluons and n_q quarks after evolution through Y [1]. These generating functions encode the full multiplicity structure of the cascade.

The distinction between quark-initiated and gluon-initiated jets plays a crucial role in the development of the cascade. Gluon jets, due to the self-interaction of gluons and their larger color factor, produce a higher multiplicity of particles compared to quark jets. This enhancement arises from the increased probability of gluon branching, leading to a more rapid development of the cascade and stronger correlations among produced particles. Consequently, gluon-induced processes dominate the multiplicity structure at sufficiently high energies, providing a fundamental justification for the Gluon Dominance Model and forming the basis for the present analysis.

The Markovian nature of the branching process leads to Chapman-Kolmogorov equations for the transition probabilities, which translate into functional equations for the generating functions. By considering the evolution over an infinitesimal interval ΔY, one obtains differential equations governing the generating functions. The evolution of these generating functions is governed by Kolmogorov-type equations, which encode the probabilistic branching dynamics of the cascade. These take the form of forward Kolmogorov equations,

$$\frac{\partial G}{\partial Y} = \frac{\partial G}{\partial u_g} w^{(g)}(u_g, u_q) + \frac{\partial G}{\partial u_q} w^{(q)}(u_g, u_q)$$

$$\frac{\partial Q}{\partial Y} = \frac{\partial Q}{\partial u_g} w^{(g)}(u_g, u_q) + \frac{\partial Q}{\partial u_q} w^{(q)}(u_g, u_q)$$

where $w^{(g)}$ and $w^{(q)}$ are the infinitesimal generating functions corresponding to gluon and quark branching processes. These functions are given explicitly by

$$w^{(g)}(u_g, u_q) = (-A - B)u_g + Au_g^2 + Bu_q^2$$

$$w^{(q)}(u_g, u_q) = (-\tilde{A}u_q + \tilde{A}u_q u_g)$$

where A, $\tilde{A}$, and B represent the probabilities per unit Y of gluon splitting, quark bremsstrahlung, and quark pair production, respectively.

The corresponding backward Kolmogorov equations, which are particularly useful for solving the system, are written as

$$\frac{\partial G}{\partial Y} = w^{(g)}[G(u_g, u_q; Y); Q(u_g, u_q; Y)]$$
$$\frac{\partial Q}{\partial Y} = w^{(q)}[G(u_g, u_q; Y); Q(u_g, u_q; Y)]$$

with initial conditions

$$G(u_g, u_q; 0) = u_g$$
$$Q(u_g, u_q; 0) = u_q$$

reflecting the fact that the cascade originates from a single parton. [1].

For the purpose of describing observable particle multiplicities, it is convenient to introduce the single-variable generating function

$$Q(z) = \sum_{n=0}^{\infty} P_n z^n,$$

which provides a complete description of the multiplicity distribution P_n. The distribution can be recovered through

$$P_n = \frac{1}{n!} \frac{d^n Q(z)}{dz^n} |_{z=0}.$$

The generating function formalism allows the systematic calculation of moments of the distribution. The factorial moments are defined as

$$F_q = \frac{d^q Q(z)}{dz^q} |_{z=1},$$

with $F_1 = \langle n \rangle, F_2 = \langle n(n-1) \rangle$. The dispersion of the multiplicity distribution is given by

$$D^2 = \langle n^2 \rangle - \langle n \rangle^2 = F_2 + \langle n \rangle - \langle n \rangle^2,$$

while the second correlation moment is defined as

$$f_2 = F_2 - \langle n \rangle^2.$$

The quantity f_2 provides a direct measure of correlations among produced particles. In the case of independent particle production, the multiplicity distribution follows a Poisson law,

$$P_n = \frac{\langle n \rangle^n}{n!} e^{-\langle n \rangle},$$

for which $F_2 = \langle n \rangle^2, f_2 = 0$. This result implies the complete absence of correlations among produced particles.

However, experimental observations show clear deviations from Poisson behavior, indicating that particle production is governed by correlated processes arising from the cascade dynamics. More generally, higher-order correlations can be characterized through cumulant moments, defined via the logarithm of the generating function,

$$K_q = \frac{d^q \ln\, Q(z)}{dz^q}\Big|_{z=1},$$

which provide a measure of genuine q-particle correlations. The ratio $H_q = K_q/F_q$ is often used to study the oscillatory behavior of correlations as a function of order.

For branching processes characterized by multiplicative growth, the Furry–Yule (or Polya–Eggenberger) distribution emerges, reflecting the self-similar nature of the cascade. A more general and phenomenologically successful description is provided by the negative binomial distribution,

$$P_n = \frac{\Gamma(n+k)}{\Gamma(k)\, n!}\left(\frac{\langle n\rangle}{k}\right)^n \left(1+\frac{\langle n\rangle}{k}\right)^{-(n+k)},$$

where the parameter k controls the width of the distribution and encodes the strength of correlations. In this case, the second factorial moment becomes

$$F_2 = \langle n\rangle^2 \left(1+\frac{1}{k}\right),$$

leading to

$$f_2 = \frac{\langle n\rangle^2}{k} > 0,$$

which explicitly demonstrates the presence of positive correlations.

An important scaling property observed in high-energy interactions is the Koba–Nielsen–Olesen scaling [2], which states that multiplicity distributions at different energies can be expressed in a universal form when scaled by the average multiplicity,

$$\langle n\rangle P_n = \Psi\left(\frac{n}{\langle n\rangle}\right),$$

where Ψ is an energy-independent function. This scaling behavior reflects the approximate self-similarity of the cascade and provides an important constraint on theoretical models.

The physical interpretation of these results is closely linked to the degree of development of the quark–gluon cascade. At relatively low center-of-mass energies $\sqrt{s}$, the evolution parameter Y is small, and the cascade undergoes only a limited number of branching steps. In this regime, the multiplicity distribution is strongly influenced by hadronization, and correlations are relatively weak. As the energy increases, the cascade becomes more developed, with gluon branching playing an increasingly dominant role due to gluon self-interaction. This leads to broader multiplicity distributions, enhanced correlations, and deviations from simple statistical models. The transition from a hadronization-dominated regime to a cascade-dominated regime is thus a key feature of multiparticle production in QCD.

Thus, the generating function formalism, combined with the stochastic description of QCD branching processes, provides a comprehensive framework for understanding multiparticle production. It establishes a direct link between the dynamics of quark–gluon cascades and observable quantities such as multiplicity distributions and correlation moments. This framework not only explains the emergence of correlations and deviations from Poisson behavior but also highlights the dominant role of gluon-driven branching in shaping the multiplicity structure, thereby forming the theoretical basis for the implementation of the Gluon Dominance Model and its comparison with experimental data.

3. Two-Stage Model and Gluon Dominance Framework

The probabilistic description of multiparticle production in terms of quark–gluon cascades provides a consistent account of the partonic stage of the interaction. However, experimental observables correspond to hadronic final states, and therefore a complete description must incorporate the transition from partons to hadrons. Since hadronization occurs in the non-perturbative regime of Quantum Chromodynamics, it cannot be derived directly from first principles and must be described phenomenologically. This leads naturally to a two-stage picture of multiparticle production, in which the evolution of the system is separated into a partonic cascade followed by hadron formation.

In the first stage, an initial parton system develops through a stochastic branching process governed by QCD dynamics, as discussed in the previous section. The cascade results in the production of a number of active partons, predominantly gluons, which act as sources for hadron production. The multiplicity distribution of these partons is determined by the dynamics of the cascade and reflects the probabilistic nature of the branching processes. Due to the self-interacting property of gluons, their contribution to the cascade is significantly enhanced, leading to the expectation that gluons play a dominant role in the subsequent particle production.

The second stage consists of hadronization, in which the produced partons transform into observable hadrons. In the Gluon Dominance Model, it is assumed that the primary sources of hadron production are the active gluons generated in the cascade, while quarks contribute mainly as leading particles. The hadronization of each gluon is treated as a stochastic process, and the number of hadrons produced from a given gluon is described by a binomial-type distribution. If Ndenotes the maximum number of hadrons that can be produced from a gluon and $\bar{n}^h$is the average number of hadrons per gluon, the probability of producing $n$hadrons from a single gluon is given by

$$P_n^{(h)} = \binom{N}{n} \left(\frac{\bar{n}^h}{N}\right)^n \left(1-\frac{\bar{n}^h}{N}\right)^{N-n}.$$

This distribution reflects the finite capacity of a gluon to produce hadrons and introduces fluctuations associated with the hadronization process.

The overall multiplicity distribution of produced hadrons is obtained by combining the partonic and hadronization stages. If $P_m^{(g)}$ denotes the probability of producing m active gluons in the cascade, and $P_n^{(h|m)}$ represents the probability of producing n hadrons from these m gluons, then the total multiplicity distribution can be expressed as a convolution,

$$P_n = \sum_{m=0}^{\infty} P_m^{(g)}\ P_n^{(h|m)}.$$

where $Q_1(z)$ is the generating function for hadron production from a single gluon. For the binomial hadronization scheme, this takes the form

$$Q_1(z) = \left(1 - \frac{\bar{n}^h}{N} + \frac{\bar{n}^h}{N} z\right)^N .$$

Thus, the full generating function for hadron production from m gluons is

$$Q_h(z) = \left(1 - \frac{\bar{n}^h}{N} + \frac{\bar{n}^h}{N} z\right)^{mN} .$$

The total multiplicity distribution is then obtained by averaging over the gluon multiplicity distribution,

$$Q(z) = \sum_{m=0}^{\infty} P_m^{(g)} \left(1 - \frac{\bar{n}^h}{N} + \frac{\bar{n}^h}{N} z\right)^{mN} .$$

Assuming independent hadronization of gluons, the conditional probability $P_n^{(h|m)}$ can be constructed from the binomial distribution associated with each gluon. This leads to a compound distribution in which fluctuations from both the cascade and hadronization stages contribute to the final multiplicity.

Within this framework, the multiplicity distribution of active gluons is often described by a distribution arising from branching processes. A commonly used form is the negative binomial distribution, which effectively captures the fluctuations generated during the cascade. The parameters of this distribution are related to the underlying dynamics of gluon branching and determine the width and shape of the multiplicity spectrum.

The model is characterized by a set of parameters that describe both the cascade and hadronization stages. The parameter k_p governs the shape of the gluon multiplicity distribution and reflects the strength of cascade fluctuations, while $\bar{m}$ represents the average number of active gluons produced in the cascade. The hadronization process is characterized by $\bar{n}^h$, the average number of hadrons produced per gluon, and N, which determines the maximum number of hadrons and controls the width of the binomial distribution. The parameter α accounts for the fraction of gluons effectively participating in hadronization, while Ω serves as a normalization factor ensuring consistency with experimental multiplicity distributions. Together, these parameters encode the interplay between cascade dynamics and hadron formation.

The two-stage formulation naturally explains several features observed in experimental multiplicity distributions. The broadening of the distributions and the presence of correlations arise from the combined effects of cascade fluctuations and hadronization. In particular, the dominance of gluons in the cascade leads to enhanced particle production, while the statistical nature of hadronization introduces additional fluctuations that modify the shape of the distribution. The resulting multiplicity spectra exhibit characteristics consistent with negative binomial behavior, reflecting the interplay between branching dynamics and hadron formation.

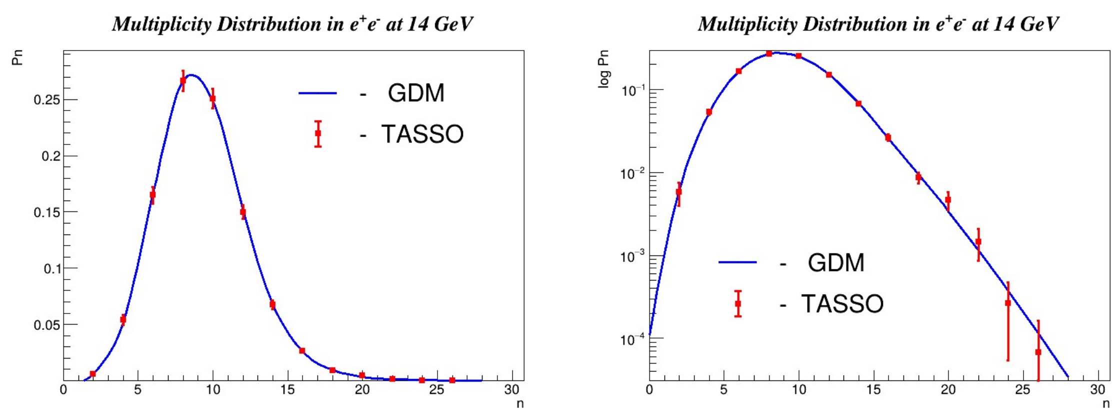
Furthermore, the model provides insight into the energy dependence of multiparticle production. At lower center-of-mass energies, where the parton cascade is not fully developed, hadronization plays a dominant role, and the multiplicity distribution is primarily determined by the properties of the hadronization process. As the energy increases, the cascade becomes more developed, leading to a larger number of active gluons and a corresponding increase in particle multiplicity. This transition from hadronization-dominated to cascade-dominated behaviour is a key feature of the Gluon Dominance Model and is reflected in the evolution of model parameters with energy.

The two-stage formulation embodied in the Gluon Dominance Model thus provides a quantitative framework in which the effects of cascade dynamics and hadronization are consistently combined. It explains the observed broad multiplicity distributions and the presence of correlations as a consequence of gluon-driven branching processes followed by statistical hadron formation. The model further predicts a transition with increasing energy from a regime dominated by hadronization to one in which the quark–gluon cascade plays a central role, thereby offering a coherent interpretation of the energy dependence of multiparticle production.

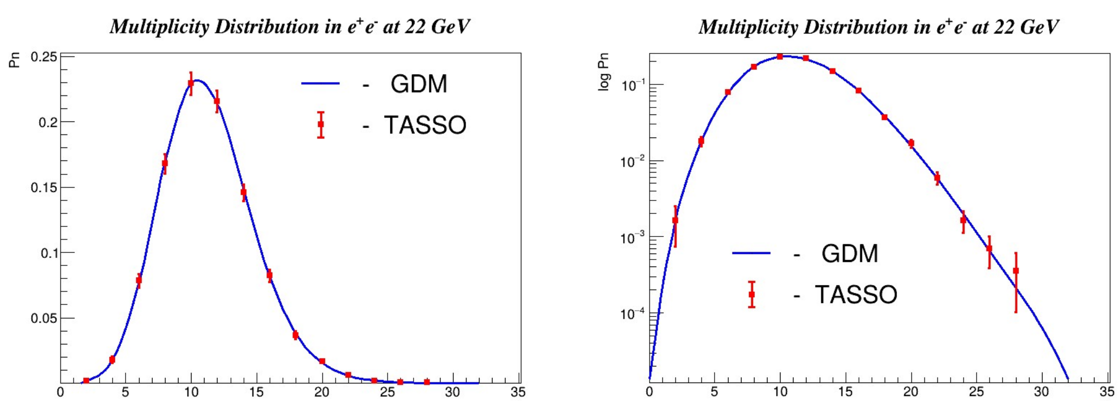
4. Analysis of Multiplicity Distributions and Energy Dependence

The theoretical framework developed in the preceding sections is applied to the analysis of experimental multiplicity distributions in e^+e^- annihilation at center-of-mass energies of 14 GeV, 22 GeV, 34.8 GeV, and 43.6 GeV. The calculations are implemented within the CERN ROOT framework using C++, where the parameters of the Gluon Dominance Model are extracted through a χ^2 minimization procedure based on the MINUIT algorithm. This enables a systematic determination of the optimal parameter set by fitting theoretical multiplicity distributions to experimental data, allowing a direct and quantitative comparison between the model and observations.

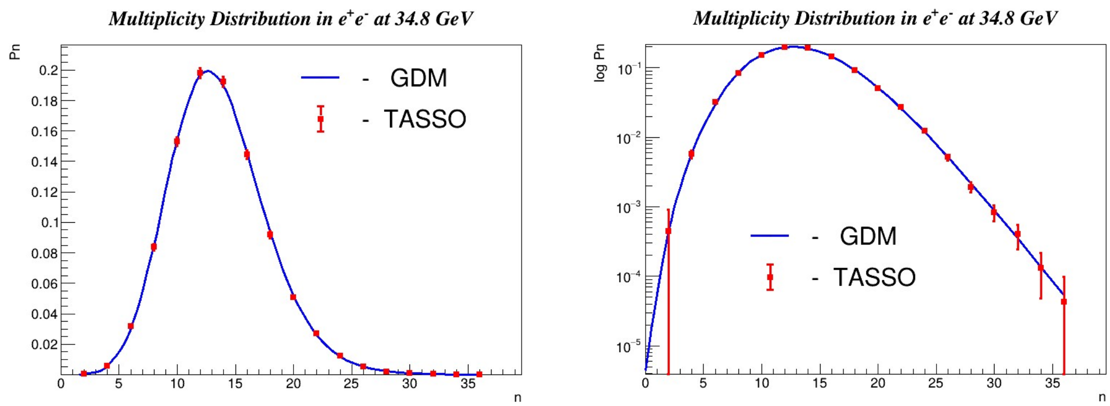
(a)



(b)



(c)



(d)

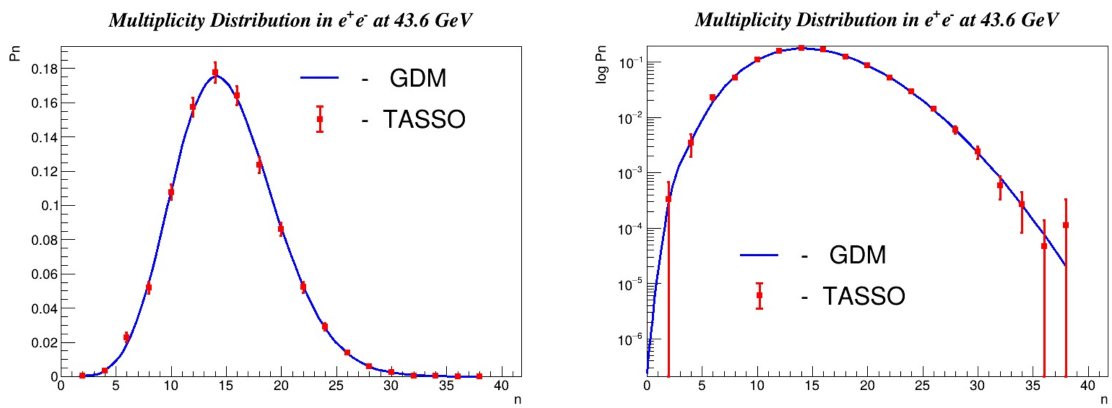


Figure 1. Multiplicity distributions in e^+e^- annihilation:
(a) 14 GeV, (b) 22 GeV, (c) 34.8 GeV, (d) 43.6 GeV.
Left: n vs P_n, Right: n vs $log\ P_n$.

The multiplicity distributions P_n are calculated for each energy using the fitted parameter values and are compared with experimental data through plots of n versus P_n and n versus log P_n, as shown in *Figure. 1* for the different energies considered. The logarithmic representation provides enhanced sensitivity to the tail of the distribution, which is particularly important at higher energies where the multiplicity spectrum broadens significantly. The agreement between theoretical curves and experimental data demonstrates that the Gluon Dominance Model successfully reproduces the essential features of multiplicity distributions over a wide energy range.

A summary of the extracted model parameters is presented in *Table 1*, including the values of k_p, $\bar{m}$, $\bar{n}^h$, N, α, and Ω for each energy. These parameters exhibit a clear dependence on the center-of-mass energy, reflecting the evolution of the particle production mechanism. In particular, the average number of active gluons $\bar{m}$increases with energy, indicating an increasing degree of parton multiplication within the cascade. The parameter N, which characterizes the hadronization stage, also shows an increasing trend, consistent with the growth in final-state multiplicity.

Energy, $\sqrt{s}$	k_p	$\bar{m}$	$\bar{n}^h$	N	α	Ω
14 GeV	80.5521	0.0816802	4.46755	27.8852	0.976056	1.99769
22 GeV	3.15105	2.40549	4.60436	26.5098	0.189238	1.99916
34.8 GeV	1.83558	1.66805	5.89256	498.352	0.183468	1.99876
43.6 GeV	5.42061	11.6116	4.90565	11088	0.0999583	2.10835

***Table 1*: Parameter values at different energies**

The behavior of the parameter k_p, associated with cascade dynamics, provides further insight into gluon branching. Although its variation is not strictly monotonic, it reflects the interplay between cascade development and hadronization effects. At lower energies, where the cascade is only partially developed, the contribution of gluon branching is limited, resulting in weaker correlations. As the energy increases, gluon-induced processes become increasingly significant, leading to a broader multiplicity distribution and enhanced correlation effects.

The multiplicity distributions exhibit clear deviations from Poisson behavior, particularly at higher energies. The observed distributions are broader and display extended tails, consistent with the characteristics of the negative binomial distribution. This behavior indicates that particle production is governed by correlated processes arising from the quark–gluon cascade rather than independent emission.

The energy dependence of multiplicity distributions further supports this interpretation. With increasing center-of-mass energy, the distributions become progressively wider, reflecting the larger phase space available for parton branching. This is accompanied by an increase in average multiplicity and a corresponding enhancement of correlation effects. These observations indicate a transition from a regime in which hadronization dominates at lower energies to one in which cascade dynamics play an increasingly significant role at higher energies.

It is also observed that the evolution of multiplicity distributions with energy is not entirely smooth. Variations in the extracted parameters and changes in the shape of the distributions suggest the presence of non-trivial structures in the underlying dynamics, which may be associated with threshold effects or changes in dominant particle production mechanisms. In particular, the region near the Z^0 boson mass scale [6] is known to exhibit distinct features in multiplicity behavior, reflecting the influence of electroweak processes and enhanced gluon radiation at higher energies.

The overall agreement between theoretical predictions and experimental data across different energies provides strong support for the Gluon Dominance Model as an effective description of multiparticle production. The results demonstrate that gluon-driven branching processes play a central role in shaping multiplicity distributions, while the interplay between cascade dynamics and hadronization determines the detailed structure of the observed spectra. The analysis thus provides clear evidence for the dominant contribution of gluons in multiparticle production in e^+e^- annihilation.

5. Conclusion

In this work, multiparticle hadron production in e^+e^- annihilation has been investigated within the framework of the Gluon Dominance Model, combining a stochastic description of quark–gluon cascades with a phenomenological treatment of hadronization. The generating function formalism provides a consistent basis for describing multiplicity distributions and establishes a direct connection between QCD dynamics and experimentally observable quantities. The numerical implementation within the CERN ROOT framework, with parameter extraction through MINUIT-based χ^2 minimization, enables a quantitative comparison between theoretical predictions and experimental data across a range of energies.

The analysis demonstrates that gluon-driven branching processes play a dominant role in shaping multiplicity distributions, leading to broader spectra and the emergence of correlations among produced particles. The observed deviation from Poisson behavior and the consistency with broader statistical distributions reflect the underlying cascade dynamics. Furthermore, the results exhibit a clear energy dependence, with hadronization effects dominating at lower energies and a progressively increasing contribution from the quark–gluon cascade at higher energies.

These findings provide a coherent interpretation of multiparticle production as a consequence of gluon-dominated cascade evolution followed by statistical hadron formation. The present study thus establishes the central role of gluons in hadron production and confirms the Gluon Dominance Model as a robust and quantitatively consistent framework for describing multiparticle production in e^+e^- annihilation.

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