UNIVERSITY OF BRISTOL

Measurement of the charged particle multiplicities at a centre of mass energy of 7 TeV at LHCb

by

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Department of Physics

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Abstract

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This thesis presents a method for unfolding the observed charged particle distributions produced from proton-proton collisions at a centre of mass energy of $\sqrt{s} = 7$ TeV at the LHCb detector. These results will help to constrain the parameters phenomenological particle production models and Monte Carlo event generators, and help to provide insight on the mechanisms behind particle production, especially in the soft QCD regime.

Acknowledgements

Contents

Chapter 1

Introduction

The LHCb collaboration is formed of more than six hundred scientists from over fifty different institutions across the globe, it is truly a testament to human innovation and cooperation. The experiment aims to address some of today's unanswered questions about our Universe, such as the observed matter-antimatter asymmetry (a term which a hundred years ago was a term known only to a few select specialists but today is familiar amongst the general public).

At the heart of the collaboration is the LHCb detector, a finely tuned machine which took over a decade to design and construct. The LHCb detector sets itself apart from the more common hermetic detectors found in operation around the LHC by its unique geometry. This is specialised to detect particles at an angle close to that of beam pipe known as the forward region - a region in which hermetic detectors tend to be insensitive. In addition to this, the production mechanism of exotic mesons such as B and D mesons are favoured in the forward region, making LHCb the current world's best environment in which to the study the decay of such mesons.

The decay processes of these rare particles are thought to hold the key to understanding the mechanisms behind the matter-antimatter asymmetry observed as well as acting as a probe for new physics via loop processes or the famous penguin processes. The unique geometry of the LHCb detector together with its outstanding primary vertex reconstruction and particle identification makes it the ideal machine for scientists at

LHCb to provide many of the world's best measurements, test the standard model and models beyond the standard model more strictly than ever before and to lead searches into new physics beyond our current understanding.

One of the key tools available to particle physicists are those of Monte Carlo simulation. This tool enables scientists to simulate physical processes and gauge how these will manifest themselves in a real life experimental situation. It is a prominent example of the process of bridging between theoretical predictions and their real world observations, a branch of Physics called Phenomenology.

The use of Monte Carlo simulations is prolific in a variety of physics analyses, typically it is used in estimating the background contributions, detector and trigger efficiencies, signal shape and sensitive studies. Such a large span of uses stresses the importance of having a reliable Monte Carlo simulation and much effort has been put into developing models that are in good agreement with measured data. Much of the challenge in this is finely tuning the ample number of parameters used in these simulators through constraints set by measured data.

Chapter 2

Background theory

2.1 The Standard Model

The Standard Model describes fundamental particles and their interactions mediated via force carrying particles. It describes electromagnetism, the weak force and the strong force.

The Standard Model is built upon the principles of Quantum Field Theory and renormalizable gauge theories developed in the twentieth century [1]. It is most commonly represented in the form of the Lagrangian formalism and is divided into the following sectors. The Electroweak sector - describing both electromagnetic forces and weak interactions, Quantum Chromodynamics (QCD) sector - describing the strong interaction and the Higg's sector - describing interactions with the Higg's field.

The Standard Model has proven to be an extremely successful theory having exceptional predictive powers - the theoretical prediction of the electron anomalous magnetic moment being in agreement with experimental data to 10 significant figures [2].

2.1.1 Fundamental Particles

The fundamental particles are categorised by several intrinsic properties which can be seen in table 2.1. By their intrinsic spin they are classified as particles with half-integer spin (fermions) and integer spin (bosons), these are outlined in the following sections.

Fermions

Fermions are further sub-divided into two groups - quarks and leptons - depending on the types of interactions they experience. Quarks have the property of colour which makes them sensitive to the strong interaction whilst leptons do not.

Both quarks and leptons are further sub-divided into three generations; the higher generations correspond to particles with higher mass states, these particles rapidly decay to the lower stable generations by the weak force.

Each fermion generation consists of a particle doublet, for example the first generation of quarks is composed of up and down type quarks. Particles in fermions doublets couple strongly to one another such that interactions between the two particle types are relatively strong in comparison to coupling between particles in different generations. This can be seen in the CKM matrix (a matrix which describing coupling between different quark types measured through experiment) where the coupling between the up and down quarks is approximately four times greater than between up and strange type quarks.

The lepton generations are made up of a charged lepton and neutrino doublet. There is no coupling between lepton generations (in contrast to quarks) in the standard model; higher generation lepton states such as the tau lepton may decay via tree processes such as a decay to its corresponding neutrino along with a $W^{\pm}$ boson (see subsection below).

The three generations together with the corresponding doublets gives a total of 6 quark flavours and 6 lepton flavours.

Bosons

The Standard Model describes two types of bosons, gauge bosons and the Higg's boson.

A gauge boson is a force carrying particle - also referred to as a force mediator - associated to a particular type of interaction e.g. gluons are associated with the strong interaction and photons are associated to the electromagnetic interaction. The term "gauge" comes from the property of the equations of motion related to a given interaction; these are invariant under "gauge" transformations which are discussed in section 2.1.3.

The Higgs boson plays a unique role in the Standard Model. Its existence supports the validity of the Higgs mechanism; a mechanism which explains why some particles are massive while others are not, in addition to why interaction strengths vary for different interaction types. On the 4th July 2012 the discovery of particle with a mass between 125 and 127 GeV was announced; on the 14th March 2013 the properties of the newly discovered particle were found to be consistent with the Higgs Boson predicted by the standard model.

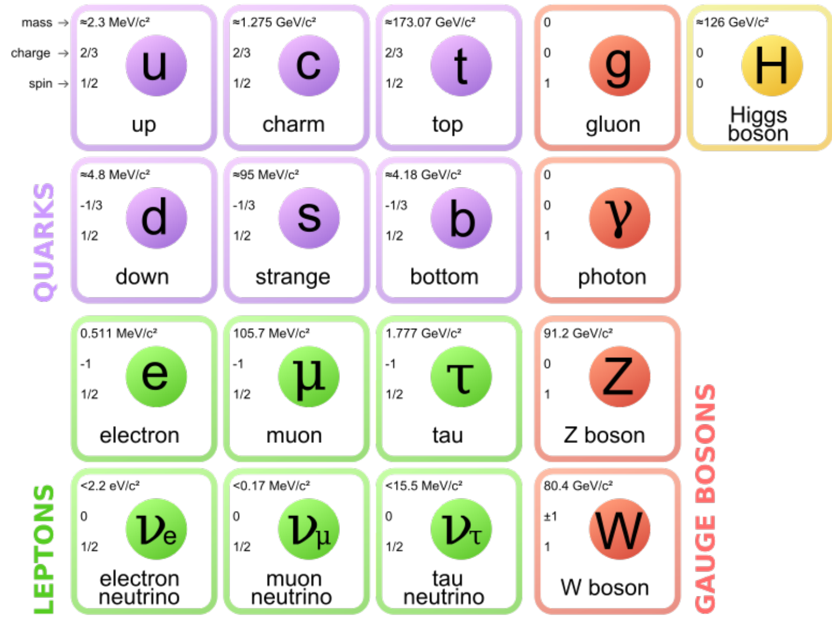


FIGURE 2.1: Table of particles in the Standard Model [3]

2.1.2 Quantum Field Theory (QFT)

Quantum field theory is built on concepts from Quantum Mechanics, Special Relativity and Classical Field Theory. Fundamental particles are described as excitations or quanta of the fields. For example, electrons are quanta of the electron field and similarly photons are quanta of the electromagnetic field i.e. interactions between electrons can be described as being a result of the interaction between the electron field and electromagnetic field. Mathematically these interactions can be described using the Lagrangian Formalism.

2.1.2.1 Lagrangian Formalism

With Lagrangian mechanics the equations of motion for a given field is derived by minimising the action $\mathcal{S}$ given by,

$$\mathcal{S} = \int \mathcal{L}(\phi, \partial_\mu \phi) \mathrm{d}^4 x \tag{2.1}$$

where $\mathcal{L}$ is the Lagrangian density, ϕ is the field and ∂_μ is the differential operator acting on the space and time coordinates of the field as seen in special relativity. By applying the condition of the Principle of Least Action, the equations of motion are given by the Euler-Lagrange equation,

$$\partial_\mu \left(\frac{\partial \mathcal{L}}{\partial(\partial_\mu \phi_i)} \right) = \frac{\partial \mathcal{L}}{\partial \phi_i} \tag{2.2}$$

2.1.3 Gauge Theories

A gauge theory is defined by a Lagrangian which is invariant under continuous local transformations of the fields or coordinates.

$$\delta \mathcal{L} = 0 \tag{2.3}$$

Each possible gauge transformations can be represented by a matrix; together these matrices form a group under matrix multiplication - the symmetry group of the gauge theory.

For each generator of the group there is an associated gauge field, for example, in QED there is one generator to the U(1) group which is associated to the electromagnetic four-vector potential field. Similarly, in QCD there are 8 generators associated to the SU(3) group corresponding to 8 gluon fields. The quanta of the gauge fields are called gauge bosons, for the previous examples these are the photon and gluons respectively.

The symmetry group for the Standard Model is U1 x SU(2) x SU(3), it is a non-Abelian group with 12 gauge fields; the corresponding gauge bosons are the photon, W+, W-, Z0 and eight types of gluon.

2.1.4 Coupling Constants

The coupling constants of a theory are dimensionless values that describe the strength of an interaction. For example the fine structure constant of QED (α) describes the strength of the electromagnetic interaction, defined as,

$$\alpha = \frac{e^2}{4\pi} \tag{2.4}$$

where e is the charge of the positron[1] and α has the value 1/137. Theories with coupling constants that have a value much less than one are said to be weakly coupled. The evolution of systems described by these theories are compatible with perturbative calculations in which the expansion is based on powers of the coupling constant. Conversely theories with coupling constants that have a value of the order of one or greater are said to be strongly coupled and are not compatible with the perturbation method.

The Standard model consists of theories with running coupling constants, which vary depending on the energy scale of a process. The behaviour of these are described by the β functions,

$$\beta(g) = \frac{\partial g}{\partial log(\mu)} \tag{2.5}$$

[1] Expressed in Heaviside-Lorentz and natural units. Unless explicitly stated otherwise all following equations will be expressed in this way

where g is the coupling constant of the theory ($g = e$ for QED) and μ is the interaction energy scale. A β function with positive values describes a coupling that increases with the energy of the process and vice-versa.

2.1.5 Quantum Electrodynamics (QED)

QED is an example of a Quantum Field Theory, it describes the electromagnetic interactions between charged fermions via the exchange of photons - gauge bosons of the theory. It is both a Quantum Field Theory as well as a Gauge Theory with a symmetry group of U(1) - an Abelian group of composed of 1 x 1 unitary matrices. The Electroweak theory of the standard model is a unification of QED and Quantum Flavour Dynamics - a gauge theory which describes the weak interaction. The Lagrangian for the QED is given by,

$$\mathcal{L} = \bar{\psi}(i\gamma^{\mu} D_{\mu} - m)\psi - \frac{1}{4} F_{\mu\nu} F^{\mu\nu} \tag{2.6}$$

where ψ is a bispinor field of spin 1/2 corresponding to the electron field; γ^{μ} are the Dirac Matrices; $\bar{\psi}$ is the Dirac adjoint spinor $\psi^{\dagger}\gamma^{0}$; D_{μ} is the gauge covariant derivative given by,

$$D_{\mu} = \partial_{\mu} + ieA_{\mu} + ieB_{\mu} \tag{2.7}$$

e is the coupling constant between the electron and electromagnetic fields - charge of an electron; A_{μ} is the covariant four-potential of the electromagnetic field generated by the electron; B_{μ} is the external field due to an external source and $F_{\mu\nu}$ is the electromagnetic field tensor given by,

$$F_{\mu\nu} = \partial_{\mu} A_{\nu} - \partial_{\nu} A_{\mu} \tag{2.8}$$

2.1.6 Quantum Chromodynamics (QCD)

QCD is a physical theory that describes the interactions between particles with the property of colour via strong interactions. It is a gauge theory with a symmetry group of SU(3) (the group of unitary matrices with a determinant of one) and describes the interactions between quark and gluon fields.

The strong force is responsible for the binding force which holds nucleons together to form the nucleus of an atom. This is due to the deeper fundamental interaction between the components of nucleons - quarks and gluons - collectively called partons. The gluons are the gauge bosons of the theory i.e. mediators of the strong force. It is a short range force having a significant effect only on scale of ~ 1 fm (about the size of the charge radius of a proton) due to the nature of its coupling. The Lagrangian of QCD is,

$$\mathcal{L} = \bar{\psi}_i i((\gamma^\mu D_\mu)_{ij} - m\delta_{ij})\psi_j - \frac{1}{4}G^a_{\mu\nu}G^{\mu\nu}_a \tag{2.9}$$

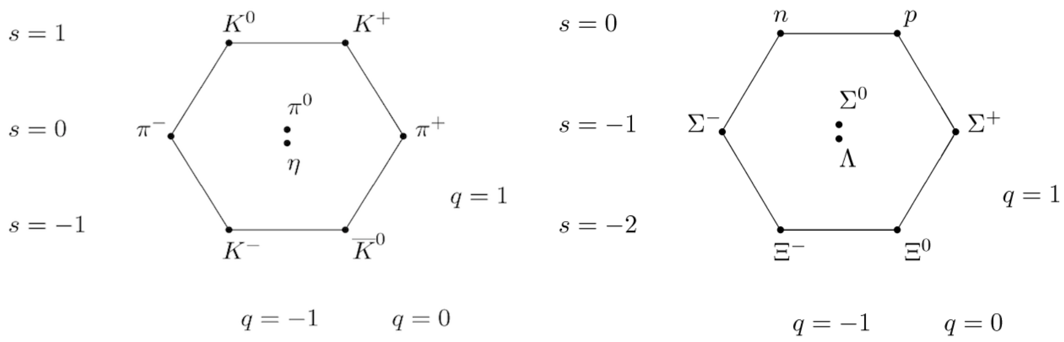
where $\bar{\psi}_i$ is the quark field and $G^a_{\mu\nu}$ is the gluon field strength tensor given by,

$$G^a_{\mu\nu} = \partial_\mu A^a_\nu - \partial_\nu A^a_\mu + gf^{abc}A^b_\mu A^c_\nu \tag{2.10}$$

where A^a_ν are the gluon fields and f^{abc} are the fine structure constants of the SU(3) group.

Quarks have been observed in two-quark bound states (mesons) and three-quark bound states (baryons); the six flavours of quarks give rise to many possible quark combinations, these combinations are commonly grouped into octets by the eightfold way, figure 2.2.

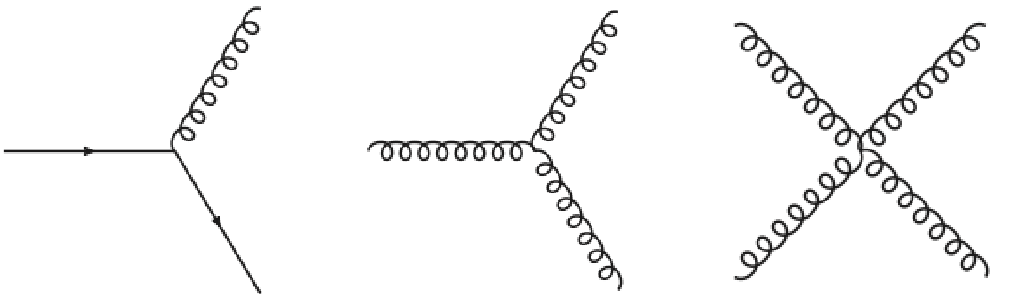
The property of colour in QCD is analogous in many ways to the role of electric charge in QED. However instead of there being one type of charge in QCD there are three types, labelled red, green, blue and their corresponding anti-colours anti-red, anti-green and anti-blue. The names of the charge types are motivated by the behaviour of coloured light such that a bound state of a red, blue and green quarks gives a net colour charge of white or colourless; a combination of colour and anti-colour is also colourless.



(A) The meson octet (two quark bound states) (B) Baryon octet (three quark bound states)

FIGURE 2.2: Eightfold method of organising quark bound states. Bound states on the same horizontal share the same strangeness and those on the same diagonals running top left to bottom right share the same charge

Each quark possesses one of the three types of colour charge; it can be either red, green or blue (similarly so for anti-quarks and the anti-colour charges). Gluons on the other hand possess a combination of colour and anti-colour charge (though these charges are not necessarily of the same colour). Since gluons are charged, QCD features some additional richness not seen in its QED counterpart. Gluons can couple with one other unlike photons which cannot, see figure 2.3.



(A) Quark-gluon vertex (B) Three-gluon vertex (C) Four-gluon vertex

FIGURE 2.3: QCD field couplings

Asymptotic freedom

The coupling constant α_s of QCD describes the strength of the strong interaction. The β function for the strong coupling constant is given by,

$$\beta(\alpha_s) = -\left(11 - \frac{2n_f}{3}\right)\frac{\alpha_s^2}{2\pi} \tag{2.11}$$

where,

$$\alpha_s = \frac{g^2}{4\pi} \tag{2.12}$$

and n_f is the number of quark flavours in the theory. Since there are six quark flavours in the standard model the values of the β function are negative i.e. the coupling constant of the strong force decreases with an increase in the energy transfer (or equivalently a decrease in the distance) of the process. The running coupling constant as a function of the energy transfer is given by,

$$\alpha_s(|q^2|) = \frac{4\pi}{(11 - \frac{2n_f}{3})\ln(|q^2|/\Lambda^2)} \quad (|q^2| >> \Lambda^2) \tag{2.13}$$

where $|q^2|$ is the energy transfer of the process and Λ is the QCD scale defined as the energy transfer at which the strong coupling constant $\alpha_s \sim 1$ and perturbative calculations with expansions of the coupling constant diverge.

This behaviour of the strong force coupling constant to become weaker at short range interactions is known as asymptotic freedom. Quarks and gluons which interact over short distances - such as at high energy collider experiments - interact very weakly and act as quasi-free particles. Since the coupling constant is small in this regime perturbative methods can also be used calculate properties of the theory.

Colour Confinement

Colour confinement is an observed phenomenon in which partons are only observed in bound colour singlets states, i.e. no individual free quarks or gluons have been observed. As quarks are separated the coupling constant increases such that the energy needed to separate them increases indefinitely. At some energy threshold the system of separating quarks will have enough enough energy to spontaneously form quark anti-quark pairs - forming a bound state with the initial quarks. This process - called hadronisation - may occur multiple times resulting in a shower of particles called a jet. Since the strong coupling constant is inherently large in these processes perturbative methods are incompatible with describing this behaviour, instead our best understanding is achieved by phenomenological models (see section 2.3.3).

2.2 QCD in Proton Collider Experiments

The complexity of QCD shown in colour confinement and the running of the strong coupling constant present additional challenges in experimental physics. In order to describe the behaviour of QCD phenomena with perturbative methods the strong coupling constant must be small such that a perturbative expansion in powers of the coupling constant converge. This is true in the case short range interactions where asymptotic freedom is present though this is not the case for long range interactions at the scale of Λ_{QCD}.

Colour confinement tells us that coloured particles can only be observed in colour singlet states called hadrons. The size of hadrons ($\sim$ 1 fm) corresponds to a energy scale of approximately 200 MeV ($\approx \Lambda_{QCD}$), hence, the observable particles associated to QCD are coupled to long range physics - i.e. incompatible with a purely perturbative description. To describe such states a combination of perturbative and non-perturbative approaches must be used.

2.2.1 Factorisation

Factorisation is the process of decoupling the hard and soft scale physics in QCD phenomena into products of hard and soft scale terms. By factorising the problem, the well understood perturbative methods can be used to calculate terms involving hard scale interactions - where $\alpha_s << 1$ - and non-perturbative methods are used to calculate the remaining contributions from soft scale physics.

The hard process is described by a matrix element calculated using the perturbative Feynman approach from the QCD Lagrangian. The soft physics is characterised by a parton distribution function which describes the density and momentum of quarks within the proton. Cross sections are then calculated by convoluting the parton level cross section with the parton distribution function.

For the process, $ij \to k$ in a proton-proton interaction, the cross-section $\sigma_{ij\to k}$ is described by,

$$\sigma_{ij\to k} = \int \mathrm{d}x_1 \int \mathrm{d}x_2 f_i^1(x_1) f_j^2(x_2) \hat{\sigma}_{ij\to k} \tag{2.14}$$

where $\hat{\sigma}$ is the cross-section for hard partonic cross-sections and f_i^1 is the parton distribution function describing the probability of finding a parton of type i in the beam proton 1 with momentum fraction x_1; similarly f_i^2 describes the distribution of partons for beam proton 2.

Due to the non-perturbative nature of parton distributions, their determination is through fits to experimental data such as from deep inelastic scattering experiments. The parton distribution functions are universal in that the parton distribution function calculated from one experiment may be used as input for another. For experiments involving different energies the behaviour of the parton distribution functions at different energy scales is described by the DGLAP evolution equations [4].

Protons accelerated to high energies are highly boosted in the laboratory rest frame, the proton is Lorentz contracted in the direction of the beamline and time dilated so that its constituent partons appear frozen, each carrying a longitudinal momentum fraction x of the total proton longitudinal momentum. The boost also ensures partons are well modelled as being collinear to its parent proton, i.e. $0 < x < 1$. The beam crossing time is short enough such that an interactions between partons in opposing beams can be modelled as a one-to-one interaction; i.e. interactions in the final state do not interfere with the initial parton-parton interaction. In this environment the proton-proton beams are well modelled as sources of quasi-free quarks and the interactions in the system are well described by a factorisation scheme.

2.3 Monte Carlo Generators

Monte Carlo (MC) generators are computational software used to simulate high energy processes. They use the principles of random sampling to emulate quantum mechanical phenomena together with the Standard Model and phenomenological models to describe particle interactions.

MC generators are important for many aspects of high energy physics. They enable physicists to develop an understanding of how physics models translate to real world experiments bridging between the theoretical and experimental aspects of high energy physics. MC generators provide physicists insight into the frequency of specific types of events as well as the angular distribution of the resultant particles. This enables physicists to estimate the signal to background ratios of specific processes and provide insight into which regions of phase space provide the greatest level of sensitivity for a given process. Understanding the distribution of the resultant particles from a given type of interaction enables highly specialist detector design optimised for sensitivity to a given process.

MC generators are extremely sophisticated programs due to the complexity of high energy process. This process is simplified by factorising the process into several steps. First a hard process is simulated with associated initial state radiation followed by the hadronisation process and final state radiation as well as beam remnants. These components are discussed in the following sections and are visualised in figure 2.4.

2.3.1 The Hard Process

The hard process is described by the parton interaction with the highest momentum transfer, it characterises the properties of the event such as the distribution of particles in the system and their energies. In general, experimentalists are interested in events involving a particular hard process, such as the production of exotic flavoured states, e.g.

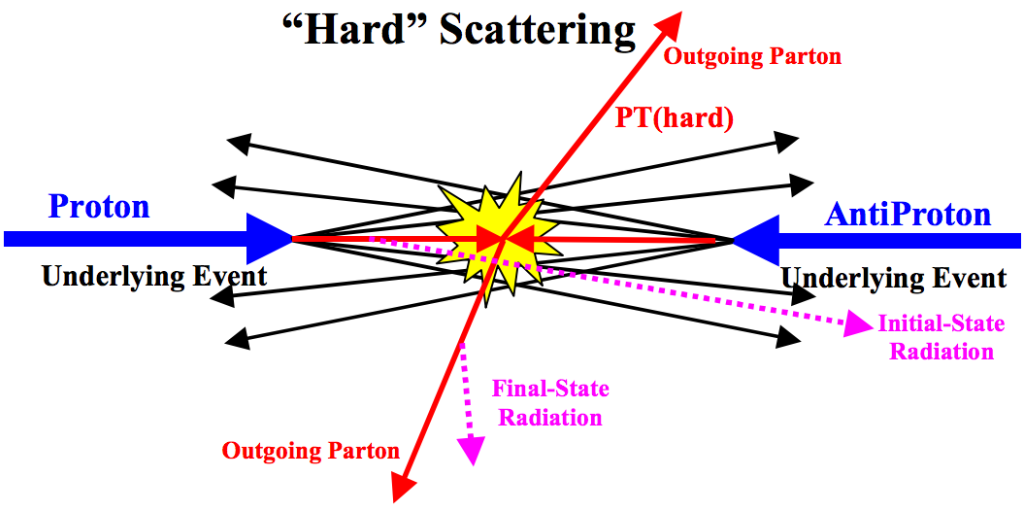


FIGURE 2.4: An event schematic demonstrating the aspects of the interaction [5]

$$gg \rightarrow c\bar{c} \tag{2.15}$$

describing the process of gluon fusion forming a charm quark-antiquark pair.

The hard process is the first stage of a MC event simulation, next a backwards time evolution is performed on the initiator partons to describe the system before the interaction. In the proton-proton event case this corresponds to the state of the incoming proton pairs. Similarly a forward time evolution is applied to the outgoing partons of the interaction to describe the final state of the system.

The forward evolution is divided into two phases, the first stage describes the radiation of quarks and gluons from the outgoing partons as a series of parton branchings evolving the system from a state with a low number of high momentum partons to a state with a high number of low momentum partons (parton shower 2.3.2). This process describes the branchings using perturbative calculations down to a momentum threshold where perturbative methods are no longer applicable. Similarly an upper momentum threshold exists; partons with a momentum greater than this threshold are assigned to the hard process of the event.

The second phase takes the output of the parton shower and evolves it into a system of colourless hadrons using non-perturbative phenomenological models via the process of hadronisation (section 2.3.3).

2.3.2 Initial and Final State Radiation

Initial state radiation is composed of partons that are emitted from the beam particles. In the case of proton beams this is modelled as virtual particles being exchanged between the quark constituents; these virtual particles primarily consist of gluons which may further radiate pairs of gluons creating a complicated state of the proton. Similarly final state radiation consists of a myriad of partons but in this case the partons originate from the out-going partons of the hard scatter and initial state radiation.

The probability for branching to occur is generally calculated in one of two ways, either with a matrix element calculated from Feynman diagrams or with the parton shower model. The parton shower model is a simplified version of the matrix element approach with approximations including a simplification of kinematics, interference and helicity structure. Though the matrix element calculations are truer to the theory of QCD, in practice the matrix elements are more difficult to calculate - especially at higher orders. The two approaches are complementary to one another and which approach is used is based on the particular situation. In general the parton shower is chosen as the first place to start due to its flexibility and simplicity whilst for precision measurements the matrix element approach is favoured.

Parton Showers

The parton shower is made up of branchings of the form $a \to bc$, e.g for quark-gluon radiation this is,

$$q \to qg$$

Each of the partons in a shower are characterised by its virtuality scale Q^2 which gives an approximate sense of its time ordering in the shower, classically it is defined as the invariant mass of the parton; under this definition a system with a low number of high mass partons evolving into a high number of low mass partons will decrease in the virtuality scale as more and more branchings occur. The Q^2 variable may also be described by other variables such as its transverse momentum which similarly decreases with the number of branchings. A maximum virtuality scale Q_{max} distinguishes partons that are involved in the hard process from those in the parton shower, also a minimum virtuality scale Q_0 sets the scale at which non-perturbative effects become significant.

Partons with $m^2 < 0$ and $m^2 \geq 0$ are described as space- and time-like respectively.

Initial State Radiation (ISR)

For initial state radiation the virtuality scale is typically associated to the mass of the parton given by the equation,

$$Q^2 = -m^2 = -(E^2 - p^2) \tag{2.16}$$

The branching evolution of initial state radiation is described by increasing values of the virtuality scale Q^2, this corresponds to a high energy parton from a beam particle emitting partons with increasing virtuality and momentum i.e. the branching partons become more space-like. The branching continues until there are enough partons with $Q^2 \geq Q^2_{\mathrm{max}}$ to initiate the hard process; thus limiting the virtuality of the system, for example, the virtuality of the partons in the process $q\bar{q} \to Z^0$ have a virtuality cut off of the order of the $2m_{Z^0}$.

In order to generate an event with a particular hard process the shower algorithm first sets the longitudinal momentums x_1 and x_2 of the incoming partons to that required by the hard process using the parton distribution function. A backward time evolution is then applied to the partons, gaining energy with each emission and decreasing in virtuality until it is compatible with a shower initiating parton in the proton.

Final State Radiation (FSR)

For final state radiation the initiating shower parton originates from the outgoing partons of the hard interaction via time-like partons. The virtuality scale for partons is typically defined by either its invariant mass or transverse momentum.

$$Q^2 = m^2 \tag{2.17}$$

or

$$Q^2 = p_\perp^2 \tag{2.18}$$

note the change in sign in the mass ordering relative to the ISR. The final state evolves with a decreasing virtuality scale - becoming more time-like. Starting from an outgoing parton from the hard process the branching results in partons with lower mass or transverse momentum depending on the choice of ordering parameter. The minimum virtuality of a parton is set by Q_0, partons which cannot branch further due to this cutoff are then used as input for the hadronisation process.

2.3.3 Hadronisation

Hadronisation is the process of evolving a system of coloured partons into colourless hadrons, photons and leptons. Hadronisation occurs in the long distance regime where perturbation theory breaks down. Instead MC generators use phenomenological models to describe the process. The two leading class of models are the string model and the cluster model, described further in the following sections.

The hadronization model used varies in importance for different observable parameters i.e. some variables are more sensitive to it than others. It has a significant effect on the particle multiplicity of an event but less so for the energy flow which is instead more sensitive to the hard process of the event. Therefore in order to constrain hadronisation models with real data, observables such as the particle multiplicity are of great importance.

The String Model

The Pythia generator uses the a string model to model the hadronization process, in this model quark bound systems are described as being connected by a string with potential,

$$V(r) = \kappa r$$

where r is the distance between the quarks and κ is the tension of the string (~ 1 GeV/fm). In this model, a system with a separating quark-antiquark has a colour flux tube joining the pair. The diameter of the tube has dimension of the typical hadronic size ($\sim$ 1fm) and is assumed to be cylindrically symmetric along its length. A massless relativistic string with no transverse degrees of freedom is used to model the axis of symmetry and the tension in the string (κ) gives the energy density of the colour flux tube.

As the distance between quarks increases the flux tube grows longer but with fixed diameter giving rise to the linear potential. This implies a distance independent force of attraction above some distance scale, it is thought that this is due to gluon self interactions originating from the three gluon vertex processes though it is not well understood.

The Cluster Model

The cluster model is based on the concept of colour pre-confinement, a property of QCD that states for partons at virtuality scales (Q) much lower than the hard process (Q_{H}),

$$Q << Q_{\mathrm{H}}$$

form colour-singlets pairs called clusters. The invariant mass distribution of the clusters falls rapidly at high masses and is asymptotically independent of the scale of the hard process (Q_{H}), depending only on Q and the QCD scale Λ_{QCD}.

To form clusters from the parton shower, the cluster model first performs gluon splitting that evolve gluons into a quark-antiquark pairs that then form the singlet cluster states with neighbouring quarks. These then undergo isotropic quasi-two-body decays into the observed hadrons.

2.3.4 The Underlying Event

The underlying event is any other activity in an event that accompanies a hard process, it contains contributions from the beam remnants - the left over proton fragments after the hard scatter - multiple parton interactions and initial and final state radiation. The hard scatter consists of the two outgoing jets, the initial state radiation leading to the hard process and the particles originating from the hard final state radiation.

The beam remnants are particles that evolves from the remainder constituents of the beam particle that do not take part in the hard process. These may be colour connected to the hard process due to colour confinement e.g. for a proton-proton interaction, a proton that initiates a hard process via a quark initiator will have remaining constituents that form a colour triplet. The colour connections are later resolved during the hadronisation process which ensures the final state of the interaction is composed of colour singlet hadrons.

2.3.5 Multiple Parton Interactions (MPIs)

Multiple parton interactions is a term used to describe a proton-proton collision in which there is more than one hard scatter between the constituent partons. Observations of MPI effects can be seen in data from hadron collisions at the Intersecting Storage Rings (ISR) at CERN [6] and the Fermilab Tevatron collider [7] [8] [9]. Soft MPI effects have been observed in proton-proton collisions at Collider Detector Fermilab (CDF) [10] [11] and CMS [12].

It is important to understand MPI for several reasons. In the case of rare and exotic physics, two simultaneous non-exotic hard interactions may lead to non-standard looking events, it follows that in order to identify rare interactions and claim a discovery, one must have some understanding of the effects from MPI. Furthermore understanding MPI gives greater insight into the physics of the proton; one of the most stable bound states and fundamental constituents of ordinary matter.

MPI models are generally dependent on modelling the impact parameter between incident protons - the minimum radial distance between their centroid trajectories. This gives the amount of overlap between the effective cross-sectional area of the protons, the smaller the impact parameter i.e. the greater the overlap, the greater the probability of interaction and thus multiple interactions.

2.3.6 Generator Comparison

Pythia

Overview

- A multi-purpose "complete" event generator.
- Commonly used in the field of high energy physics.
- Emphasis on simulating collisions between elementary particles, e.g. e^+e^- and pp interactions.
- Uses the Lund model for hadronisation.
- JETSET is merged into PYTHIA.

Factorisation

- Interactions are complicated
- Interactions can be simplified by breaking the interaction into stages (factorisation).
- The output from one stage serves as input for the next
- e.g. Hadronic events at LEP

- The main (hard) interaction is described by $e^+e^- \rightarrow Z^0 \rightarrow q\bar{q}$
- Bremsstrahlung-type modifications i.e. the emission of additional final-state particles by branchings such as $e \rightarrow e\gamma$ and $q \rightarrow qg$

Lund Model / String fragmentation

- Long-range confinement forces are allowed to distribute the energies and flavours of a parton configuration among a collection of primary hadrons.
- Predictions were confirmed by e+e- annihilation data at 30GeV, whence gained widespread acceptance.
- Currently the most complex and widely used fragmentation model.

Fragmentation vs Hadronisation

- Hadronisation is the process of transforming colourless hadrons from coloured partons, i.e. quarks and gluons
- Hadronisation is made up of fragmentation and decay
- Fragmentation is the break up of high mass coloured states into a system of colourless hadrons, e.g. jet -¿ hadron + remainder jet.

Pythia 6

Pythia 8

Pythia LHCb

EPOS

2.4 Minimum bias data

To minimise the bias of data from inelastic collisions collected from collider experiments, experimentalists use a trigger with a minimal set of criteria - generally called the minimum bias trigger. This trigger will typical involve requirements such as a minimum number of hits in an event or an event with at least one reconstructed track. Biases are still present due to collisions that are not detectable such as collisions that result in particles with trajectories collinear to the initial trajectory of the beam particles; these particles continue along the beam pipe leaving no sign in the sensitive components of the detector.

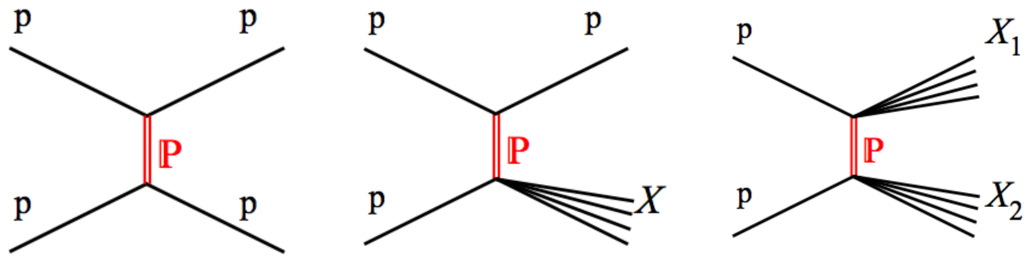
Collisions at the LHC can be classified into elastic (in which no additional particles are produced and inelastic) and inelastic collisions,

$$\sigma_{tot} = \sigma_{elastic} + \sigma_{inelastic} \tag{2.19}$$

which can be further classified into diffractive and non-diffractive collisions,

$$\sigma_{inelastic} = \sigma_{non-diffractive} + \sigma_{single-diffraction} + \sigma_{double-diffraction} \tag{2.20}$$

Diffractive collisions involve collisions that do not transfer colour between the beam particles and are characterised by events with large rapidity gaps with no hadronic activity. They can involve the break up of one of the incoming protons (single diffraction) or both (double diffraction, see figure **??**). The events typically selected by a minimum bias trigger are made up of non-diffractive inelastic events with a small contributions from diffractive collisions.



(A) Elastic scattering, $p + p \rightarrow p + p$

(B) Single diffractive scattering, $p + p \rightarrow p + X$

(C) Double diffractive scattering, $p + p \rightarrow X + X'$

FIGURE 2.5: Examples of elastic and inelastic proton-proton interactions via the exchange of a pomeron [13].

Minimum bias data is dominated by soft QCD physics characterised by low p_T particles and long interaction distances. This property of minimum bias data makes it the ideal region in which to validate, tune and develop phenomenological models e.g. particle production and the structure of the proton. Furthermore minimum bias data is a good approximation of the underlying event (see section 2.3.4) which accompanies a hard scale scatter; a good understanding of this translates to a good understanding of the associated hard energy scale physics such as the rare B decays integral to understanding matter and anti-matter physics.

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