JOINT INSTITUTE FOR NUCLEAR RESEARCH
Djelepov laboratory of Nuclear Problem

FINAL REPORT ON THE SUMMER STUDENT PROGRAM

The Effect of Colour Reconnection

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Content

Abstract

The CR effect is currently one of the most poorly studied effects of modern physics. Study of the effect is presented in this report. Pythia 8 tools were used to generate random events that occur when an electron-positron pair collides. With the help of a package of object-oriented programs and libraries, ROOT conducted experimental data.

Introduction

The Standard Model of particle physics is the theory describing three of the four known fundamental forces (the electromagnetic, weak, and strong interactions, and not including the gravitational force) in the universe, as well as classifying all known elementary particles.

All matter around us is made of elementary particles, the building blocks of matter. These particles occur in two basic types called quarks and leptons. Each group consists of six particles, which are related in pairs, or “generations”. The lightest and most stable particles make up the first generation, whereas the heavier and less stable particles belong to the second and third generations. All stable matter in the universe is made from particles that belong to the first generation; any heavier particles quickly decay to the next most stable level. The six quarks are paired in the three generations – the “up quark” and the “down quark” form the first generation, followed by the “charm quark” and “strange quark”, then the “top quark” and “bottom (or beauty) quark”. Quarks also come in three different “colours” and only mix in such ways as to form colourless objects. The six leptons are similarly arranged in three generations – the “electron” and the “electron neutrino”, the “muon” and the “muon neutrino”, and the “tau” and the “tau neutrino”. The electron, the muon and the tau all have an electric charge and a sizeable mass, whereas the neutrinos are electrically neutral and have very little mass.

Fig. 1. Particles of Standard model

In particle physics, hadronization (or hadronisation) is the process of the formation of hadrons out of quarks and gluons. This occurs after high-energy collisions in a particle collider in which quarks or gluons are created. Due to colour confinement, these cannot exist individually. In the Standard Model they combine with quarks and antiquarks spontaneously created from the vacuum to form hadrons. The QCD (Quantum Chromodynamics) of the hadronization process are not yet fully understood, but are modeled and parameterized in a number of phenomenological studies, including the Lund string model and in various long-range QCD approximation schemes.

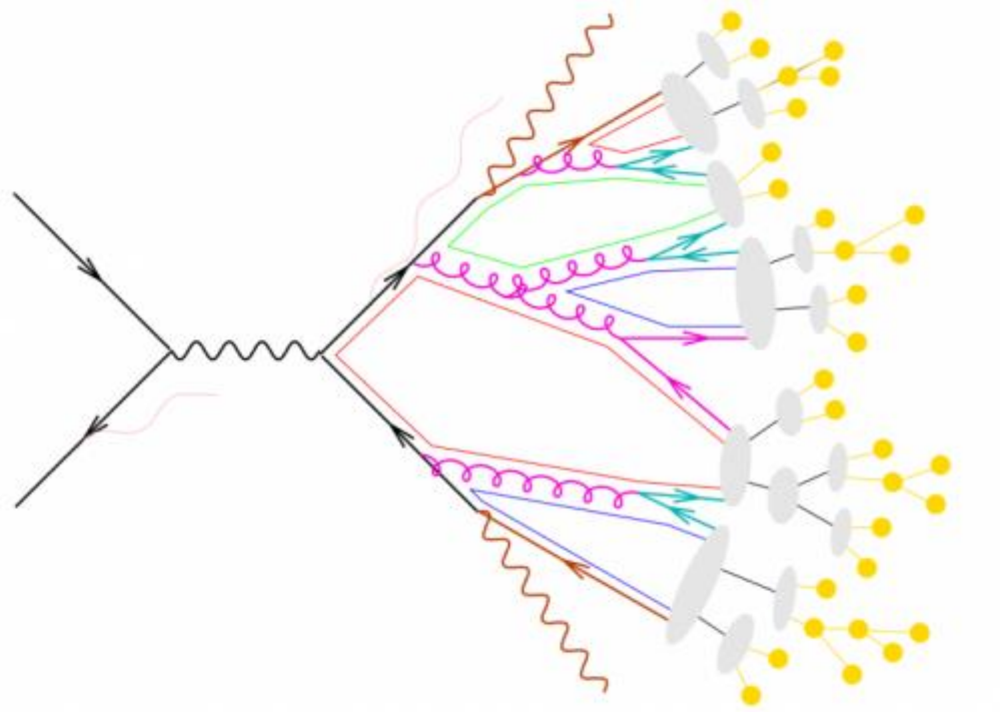

Fig. 2. Hadronization model

The tight cone of particles created by the hadronization of a single quark is called a jet. In particle detectors, jets are observed rather than quarks, the existence must be inferred. The models and approximation schemes and their predicted jet hadronization, or fragmentation, have been extensively compared with measurement in a number of high energy particle physics physics experiments.

Work

The effect of Colour Reconnection

Under certain conditions, as a result of hadronization, the effect of CR. The term "colour reconnection" or "interconnection" is a generic name covering:

a) quantum short-distance effects due to exchanges of perturbative gluons between the two initial qq¯ systems and b) long-distance effects in the parton-to-hadron transition phase caused by a large overlap between the products of the two decays (non-perturbative rearrangement/reconnection).

Colour reconnection effects in perturbative phase are expected to be small. On the other hand, significant interference is expected in the hadronisation process, which can be estimated only in the context of specific models.

Number of schemes of CR effects were developed and some of them were implemented in most of the very successful models describing the e+ e− → hadrons process.

First colour reconnection effects were introduced and observed for charmonium production in weak B decay to J/φ, in where occurs a cross-talk between two original colour singlets, ¯c + s and c+ spectator.

Quantum chromodynamics (QCD) (the theory of the strong between quarks and gluons, the fundamental particles that make up composite hadrons such as the proton, neutron and pion) it does not give a full explanation of this effect.

Our current understanding of QCD does not provide a unique recipe for CR. Therefore the best we can do is to contrast different plausible scenarios, and let data be the judge what works and what does not.

Several models have been included in the widely used event generations PYTHIA, ARIADNE and HERWIG. The models are based on different philosophies and include various assumptions. Two types of the models SKI and SKII (Sjostrand-Khose) were developed for W mass uncertainty studies at LEP2. The models are based on the Lund fragmentation picture which are implemented at the PYTHIA Monte Carlo program. In these models colour reconnection occurs for overlapping or crossing strings stretched between two qq¯ systems. The models cannot be tuned with Z^0 data. They follow the space time evolution of the strings and they allow local reconnection if the strings overlap or cross depending on the string definition. In the model SKI the probability for reconnection to occur is given by preco = 1 − exp(−T k_I). The quantity T is the space-time overlap integral between the colour flux tubes that are stretched between quarks and gluons originating from the perturbative phase of the two hadronic W decays, and k_I is an adjustable parameter of the SKII model, thus allowing to vary the fraction of reconnection events in the Monte-Carlo simulation. The reconnection occurs when these tubes overlap and only one reconnection is allowed, the one with the largest overlap volume. In the models SKII and SKII0 the strings have no lateral extent. The reconnection occurs, with unit probability, when they cross. In SKII the first crossing is taken while in SKII0 the reconnection is chosen if it reduces the total string length (λ). In the SKII scenario, the strings have negligible thickness and a unit reconnection probability which is allowed to occur at the first string crossing which reduces the total string length of the system.

The model GAL (Generalised Area Law), is implemented within and based on the Lund string fragmentation model as well. The reconnection probability for this model is given by $P^{reco} = R_0(1 - \exp(-b\Delta A))$, where ΔA is the area difference between the two configurations, with and without CR (in energy momentum coordinates), b is a phenomenological parameter of the order 0.6 GeV $^{-2}$ and R_0 is tunable parameter of the order $1/N_C^2 = 0.11$.

The model GH is also implemented in the Lund string fragmentation framework. A reconnection is chosen if it reduces the total string length. This model corresponds to the scenario originally imple3 minted in ARIADNE.

The ARIADNE Monte Carlo program utilizes the dipole cascade model. Colour reconnection is implemented at the end of the parton shower if it leads to a reduction in the string length (AR1, AR2, AR3 models).

Multiple reconnection per event are permitted. They may occur within a single $q\bar{q}$ system which is AR1 model. In the AR2 model, applicable to $qq\bar{q}\bar{q}$ events, reconnections are only allowed for gluons with energies less than 2 GeV. The AR3 model, which imposes no such restriction, is disfavoured on both theoretical and experimental grounds. A colour reconnection scheme is also implemented in HERWIG which is an alternative to string fragmentation, the cluster model. After showering the gluons are split nonperturbatively into $q\bar{q}$ pairs and colour singlet clusters are formed, which then decay into a small number of hadrons. Colour reconnection would change the cluster mass, leading to an increase in the multiplicity predicted by the HERWIG CR model with respect to the nonreconnected scenario. In string-based models, on the other hand, colour reconnection tends to minimise the string length, which is correlated with the string energy, and leads to a decrease in multiplicity.

The VNI (parton-shover cascade) Monte Carlo program implements a model from Ellis and Geiger, which is the only model to allow for a colour-octet reconnection scenario and which predicts potentially large effects; however, the LEP experiments have not been able to reproduce the published predictions with the current versions of VNI.

The Pythia 8 for The Effect of CR

Of all the models presented, there are only two somewhat motivated, models implemented: the original PYTHIA scheme and a new scheme that tries to incorporate more of the colour knowledge from QCD.

The original PYTHIA scheme relies on the PS-like colour configuration of the beam remnant. This is combined with an additional step, wherein the gluons of a lower-pT MPI system are merged with the ones in a higher-pT MPI. A more detailed description of the merging can be found below. Relative to the other models it tests fewer reconnection possibilities, and therefore tends to be reasonably fast.

The Pythia8 Monte Carlo (MC) event generator is used extensively in ATLAS simulation. The modelling of multiple parton interaction (MPI) and colour reconnection (CR) in the Pythia8 generator is especially important to describe minimum-bias (MB) and underlying event (UE) observables, which is necessary for using Pythia8 as a standalone generator, or in conjunction with mulileg/multiloop matrix element generators.

The new scheme [Chr14a]relies on the full QCD colour configuration in the beam remnant. This is followed up by a colour reconnection, where the potential string energy is minimized (ie. the lambda measure is minimized). The QCD colour rules are also incorporated in the colour reconnection, and determine the probability that a reconnection is allowed. The model also allows the creation of junction structures.

In addition to the two models described above, a simple model is implemented, wherein gluons can be moved from one location to another so as to reduce the total string length. This is one out of a range of simple models developed to study potential colour reconnection effects e.g. on top mass, not from the point of view of having the most realistic description, but in order to probe the potential worst-case spread of predictions. All of these models are made available separately in include/Pythia8Plugins/ColourReconnectionHooks.h, with the setup illustrated in examples/main29.cc, but only the gluon-move one is sufficiently general and realistic that it has been included among the standard options here.

Root

As we know, Pythia is used to generate random events, ROOT is advisable to conduct data processing.

A modular scientific software framework. It provides all the functionalities necessary to deal with large data processing, statistical analysis, visualization and storage. It is mostly written in C ++ but is integrated with other languages.

It provides platform independent access to a computer's graphics subsystem and operating system using abstract layers. Parts of the abstract platform are: a graphical user interface and a GUI builder, container classes, reflection, a C++ script and command line interpreter (CINT in version 5, cling in version 6), object serialization and persistence.

The packages provided by ROOT include those for:

- Histogramming and graphing to view and analyze distributions and functions,
- curve fitting (regression analysis) and minimization of functionals,
- statistics tools used for data analysis,
- matrix algebra,
- four-vector computations, as used in high energy physics,
- standard mathematical functions,
- multivariate data analysis, e.g. using neural networks,
- image manipulation, used, for instance, to analyze astronomical pictures,
- access to distributed data (in the context of the Grid),
- distributed computing, to parallelize data analyses,
- persistence and serialization of objects, which can cope with changes in class definitions of persistent data,
- access to databases,
- 3D visualizations (geometry),
- creating files in various graphics formats, like PDF, PostScript, PNG, SVG, LaTeX, etc.
- interfacing Python and Ruby code in both directions,
- interfacing Monte Carlo event generators.

A key feature of ROOT is a data container called tree, with its substructures branches and leaves. A tree can be seen as a sliding window to the raw data, as stored in a file. Data from the next entry in the file can be retrieved by advancing the index in the tree. This avoids memory allocation problems associated with object creation, and allows the tree to act as a lightweight container while handling buffering invisibly.

Data processing in ROOT can not be performed without installing Pythia. Pythia is the main tool for studying the effect of CR. Before you start working with PYTHIA, you need to perform the following actions (on a Linux or Mac OS X system):

1. Download the pythia8235.tgz file to the appropriate location.

2. Unarchive and expand it with tar xvfz pythia8235.tgz.

3. Next, you need to go to the pythia8235 directory created in this way.

If there is a problem with the installation, the program suggests reading the README file, which details the instructions for assembling all parts.

4. The transition to the subdirectory of the examples is made.

Results of Study of CR

As mentioned earlier, the Pythia 8 program allows you to generate events that occur as a result of a proton-proton pair collision. At an energy of 8 TeV, histograms are constructed in ROOT. This happens by assigning a variable to the parameter, which is specified below:

```
    // Histograms for current scenario.
    Hist nRecH(  "number of top reconnections",  100,  -0.5, 99.5);
    Hist nchH(   "charged multiplicity",         100,   -1., 799.);
    Hist nJetH(  "jet multiplicity",              20,  -0.5, 19.5);
    Hist mWH(    "reconstructed W mass",         100,   40., 140.);
    Hist mTH(    "reconstructed t mass",         100,  120., 220.);
    Hist mWerrH( "reconstructed W mass error",   100,  -10.,  10.);
    Hist mTerrH( "reconstructed t mass error",   100,  -20.,  20.);
    Hist pTTH(   "reconstructed pT_t",            11,    0., 275.);
    Hist mTpTH(  "reconstructed delta-m_t(pT_t)", 11,    0., 275.);
```

Fig. 4. Fragment of the program with the specified parameters

```
    double Rtpt;
    double RmWH;
    double NmTH;
    T->Branch ("RmWH",&RmWH,"RmWH/D");
    T->Branch ("Rtpt",&Rtpt,"Rtpt/D");
    T->Branch ("NmTH",&NmTH, "NmTH/d");
```

Fig.5. Creating "branches" on a tree in ROOT

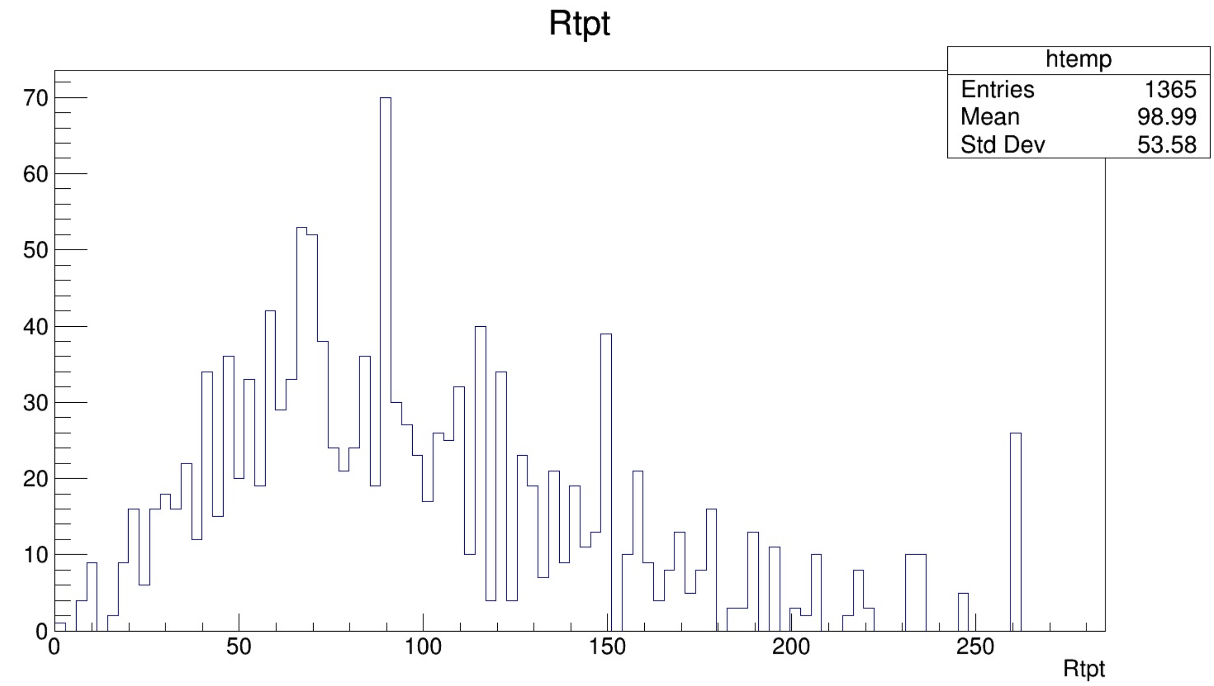

Fig. 6. Histogram for tpt with LOOP = 1

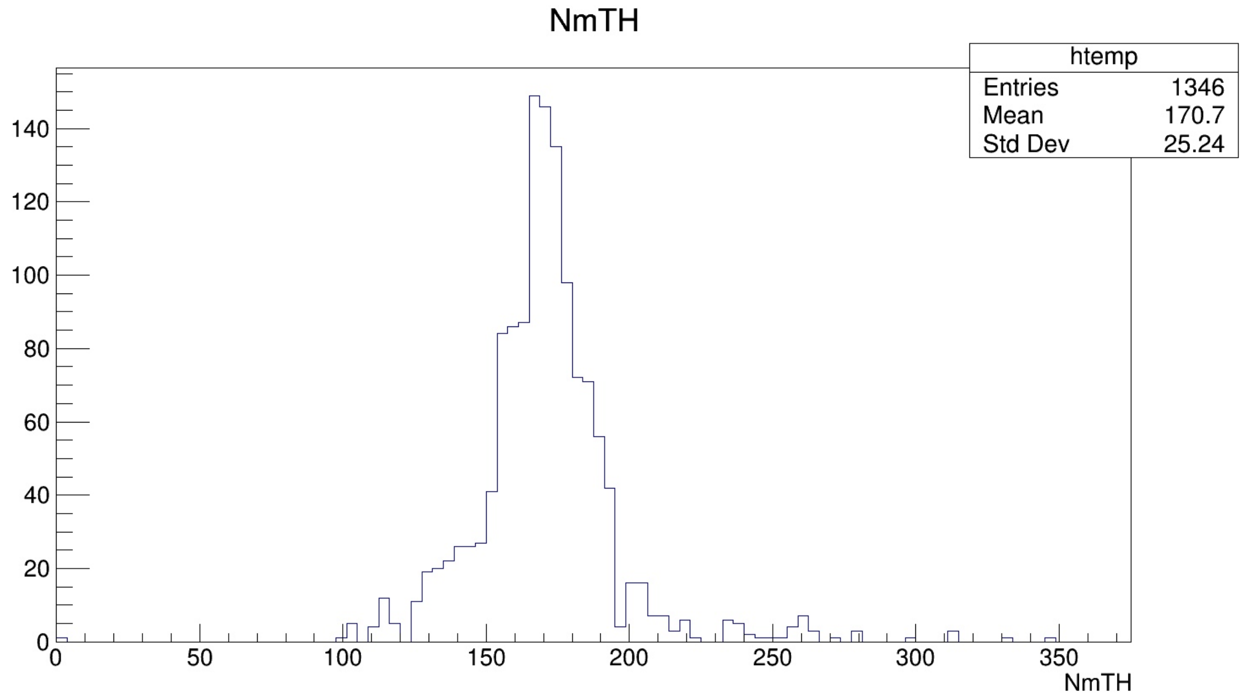

Fig. 7. Histogram for mTH with LOOP = 1

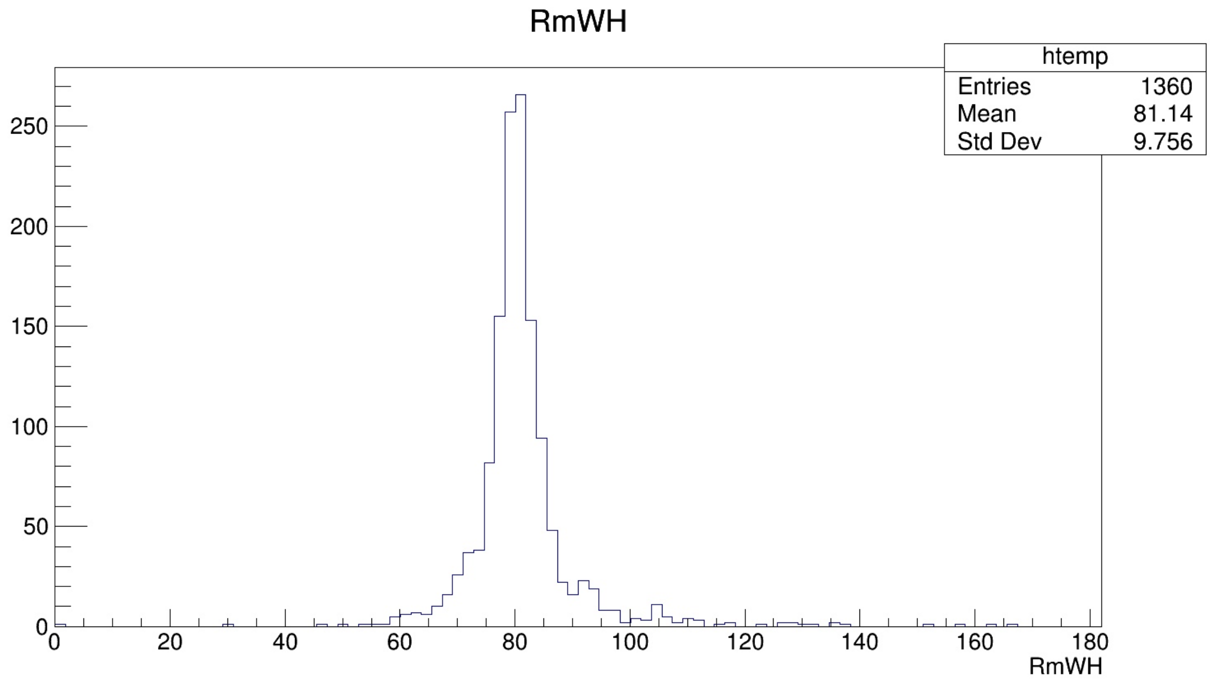

Fig. 8. Histogram for mWH with LOOP = 1

Conclusion

During the summer student program, the Standard Model was studied in more detail. The standard model includes many different subtopics, one of which is the "CR effect", which is one of the elementary particles little studied in physics.
To study this effect, it was necessary to master PUTHIA 8, as well as use libraries ROOT for building histograms.

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Stay in Dubna was for me a place where I want to return for new experience and new knowledge.

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