QCD cross section measurements with the OPAL and ATLAS detectors

Abstract of Ph.D. dissertation

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Debrecen, 2008

1 Introduction

Our understanding of the most basic constituents and laws of the Universe has improved enormously over the last few decades thanks to the experiments performed at the highest achievable energies. From the large number of observations a single theory was born that could explain all the observed phenomena, called the Standard Model of Particle Physics – the Standard Model for short.

While the Standard Model is supported by a large number of experimental observations, it has also a few shortcomings. Some of the most important problems can be summarised as follows:

- How is the mass of elementary particles generated? The gauge symmetries upon which the Standard Model is built, don't allow particles to have a mass. The Standard Model explains the observed weight of the elementary particles by a local symmetry breaking, that generates masses for the particles. As a "side-effect", this model predicts the Higgs particle that has not been experimentally observed yet.
- Is it possible to unite the electro-weak and strong interactions – and maybe even gravity – into a single theory? Our findings show that the elementary interactions become similar to each other at increasingly high energies. But the Standard Model in its current form can not describe this unification of the forces.
- What is dark matter made of? Cosmological observations suggest that the matter that we can see, makes up only about 15% of the matter in the Universe. The other 85% of matter, the gravitational force of which we can see, is currently invisible to us, and the Standard Model gives no explanation to its existence.

There are currently a multitude of theories which provide solutions for these issues. Perhaps the most acknowledged ones are the supersymmetry (SUSY) theories. While these theories provide solutions to the aforementioned problems, they also suggest the existence of yet unseen particles and interactions.

All of the large particle physics experiments of the last decades were designed to test the predictions of the Standard Model at higher and higher energies, and to look for signals of physics beyond the Standard Model. The Large Electron Positron Collider (LEP) provided the first precision measurements of the properties of the weak bosons, and was used throughout its lifetime to study many Standard Model processes.

In 2003 I joined the work of one of the experiments that was built at LEP, the OPAL experiment. I started working in the two-photon working group, studying the interactions of high energy photons with each other.

The most powerful particle accelerator ever built – the Large Hadron Collider (LHC) – is now entering its turn-on phase. The main goals of the LHC are to find the Higgs boson – or to prove that it does not exist –, verify predictions of the Standard Model at the highest energies, and to look for the predicted new particles and interactions.

In 2004 I became a member of the ATLAS collaboration, building the largest experiment for the LHC, the ATLAS detector. I joined the trigger group, working for the most part on the Level-1 and muon triggers, and got involved in the work of the bottom and top quark physics groups.

2 Standard Model processes under study

2.1 Photon–photon interactions

The photon is the gauge boson of quantum electro-dynamics (QED) and mediates the electromagnetic force between charged particles. In QED interactions, the photon can be regarded as a point-like, structure-less object, called the *direct*, or *bare* photon. Because QED is an abelian gauge theory, the photon has no self-couplings, and to our current understanding, the photon has no mass.

While the direct photon shows no structure, following the Heisenberg uncertainty principle, the photon is allowed to violate the energy conservation rule for a short time. In this time the photon is allowed to fluctuate into a fermion–anti-fermion pair carrying the same quantum numbers as the photon. During this fluctuation one of the fermions may interact via a gauge boson with another particle, and the fermion can be extracted from the photon, with the photon getting *resolved* and revealing its structure. At the LEP ring the photon–photon interactions could be studied in the following process:

$$\mathrm{e}^+\mathrm{e}^- \rightarrow \mathrm{e}^+\mathrm{e}^-\gamma^*\gamma^* \rightarrow \mathrm{e}^+\mathrm{e}^- X, \qquad (1)$$

where the electrons each emit a virtual photon, which produce an X final state, and the electrons leave the interaction without being annihilated.

2.2 Rare B-meson decays

The expected rate of B-hadron production will be enormous at the LHC. It is expected that about every hundredth proton–proton collision will produce a $b\bar{b}$ quark-pair. This will provide a possibility for many precision measurements using b quarks, and to observe B-meson decays with very small branching ratios. The decays that can be studied the easiest, are of the type:

$$B_{d,s} \rightarrow \mu^+\mu^-(X). \tag{2}$$

Such decays include flavour changing neutral currents (FCNC) and are strongly suppressed in the Standard Model. However, in many extensions of the Standard Model the branching ratios can be enhanced, by providing more channels for the decays. This means that any deviations from the Standard Model predictions for these branching ratios can be strong indications of *New Physics*[1]. To measure the branching ratios of these rare decays at high precision, the efficiency of the event selection has to be well understood and measured.

2.3 Top quark physics

The LHC will be a top quark factory, expected to produce millions of $t\bar{t}$ quark pairs. This opens up a new era in precision measurements involving the top quark.

The top quark is the $Q = 2/3$ and $T_3 = +1/2$ member of the weak-isospin doublet also containing the bottom quark. It is the most recently discovered (1995) elementary particle, although its existence was suggested by the Standard Model ever since the discovery of the bottom quark (1977). The large mass of the top quark (172 GeV) suggests that it might play a special role in nature, especially in various *New Physics* theories.

Measuring the cross section of $t\bar{t}$ production will be one of the first things to be done with early LHC data. Many calculations exist for this cross section, all of them suggesting a value of $\sigma_{t\bar{t}} \approx 820$ pb. To measure such an absolute production cross section, every step in the event selection has to be well understood.

3 Experiments

In all the modern, general purpose particle physics experiments the concept is very similar. An interaction is produced between particles at high energies by either colliding beams of particles or directing a single particle beam at a fixed target, and then all the properties of the out-going particles are measured by various detectors. I have worked in the collaboration of two such detector systems, the OPAL and ATLAS detectors as part of my thesis.

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[1] I refer to all processes not described by the Standard Model, as *New Physics*.

3.1 The OPAL detector

OPAL (Omni-Purpose Apparatus for LEP) was one of the four detector systems built for the LEP accelerator. It was a general purpose detector designed to study a wide variety of interactions occurring in e^+e^- collisions. The detector was first used in 1989, and with some upgrades it was in operation until the closure of the LEP accelerator at the end of 2000.

The detector system had the following types of sub-detectors for measuring the properties of particles produced in the collisions of electrons and positrons:

- The tracks of charged particles were recorded by a system of high-precision drift chambers. As an upgrade, to measure the tracks with high precision close to the interaction region, a silicon micro-vertex detector was installed as the innermost component of the tracking detectors.
- The total energy of electrons and photons was measured by an electromagnetic calorimeter using lead glass as active material.
- The total energy of hadrons was measured by a hadron calorimeter that used the iron of the magnet return yoke as absorber and multi-wire detectors put between the iron slabs.
- The tracks of muons leaving the detector were recorded by the muon spectrometer covering the outside of OPAL.

3.2 The ATLAS detector

ATLAS (A Toroidal LHC ApparatuS) is one of the two general purpose detectors built for the LHC. Its main goal is to make it possible to detect the Standard Model Higgs-boson in the proton–proton collisions produced by the LHC at 14 TeV centre of mass energy. The detector of course also aims at detecting a large number of other – new – phenomena.

The main components of the detector are as follows:

- The tracks of charged particles are recorded in the Inner Detector using pixel- and silicon microstrip trackers in conjunction with a Transition Radiation Tracker.
- The energy of electrons and photons is measured by a lead – liquid argon based calorimeter.
- The energy of hadrons is measured by two different detector types. In the barrel part of the detector a sampling calorimeter built from lead and scintillating tiles is used. In the endcap parts of the calorimeter liquid argon detectors are used.

- The momentum of muons is measured by measuring their deflection in toroidal magnetic fields. The muon tracks are detected by various types of gas detectors.

Event selection is very crucial at the LHC because of the high rate of events produced by the accelerator. To only record events with the highest probability to detect new phenomena with, a 3 level trigger system is used by ATLAS. This system selects 200 events, from the 40 million produced every second, to be saved for subsequent analysis.

4 Results

The scientific results of my doctoral thesis can be summarised as follows:

1. **I compared several advanced methods to separate the events coming from photon–photon interactions from dominant background processes in the OPAL experiment. I found that the most reliable method for selecting high energy photon–photon events was a likelihood based selection. [1]**

At high centre of mass energies at LEP, events having a low-p_{T} jet are dominated by two-photon interactions. This makes the selection of two-photon events with a jet having $p_{\mathrm{T}}^{\mathrm{jet}} < 10$ GeV rather easy. However, events having jets with $p_{\mathrm{T}}^{\mathrm{jet}} > 20$ GeV are very strongly dominated by $Z^0/\gamma^* \rightarrow q\bar{q}$ events. For this reason special care had to be taken when selecting energetic two-photon events.

I evaluated the performance of a Neural Network based event selection code (used by the b-physics group of OPAL) and one based on maximum likelihood distribution functions, and compared them to an event selection based on cuts on event quantities. The selection technique using maximum likelihood distribution functions proved to be the most stable, providing much better signal to background ratio than the simple cut based selection, generally used in the OPAL two-photon group.

2. **I calculated the inclusive jet production cross section in photon–photon collisions in the OPAL experiment from the data taken between 1998 and 2000. [1, 4]**

I analysed the data collected by OPAL between 1998 and 2000 at centre of mass energies $\sqrt{s_{\mathrm{ee}}} = 189 - 209$ GeV that represents a total integrated luminosity of 593 pb^{-1}.

I selected high-energy photon–photon events as described in the previous point, then extracted the inclusive jet production cross section by subtracting the estimated remaining background from the $p_{\mathrm{T}}^{\mathrm{jet}}$ distribution and normalising it to the total integrated luminosity of the data sample.

Special care had to be taken to estimate the values of systematic uncertainties on the result. The estimation took into account among others the expected uncertainty of the energy calibration of the electromagnetic calorimeter, of the subtraction of the expected background, and of the event selection cuts chosen. Finally, to be able to compare the extracted cross section with next-to-leading-order (NLO) calculations, I estimated the values of hadronisation corrections that have to be applied to the NLO cross section curve.

I have found good agreement between the measurement and the cross section predicted by the calculations. The final plot comparing the extracted cross section as a function of $p_{\mathrm{T}}^{\mathrm{jet}}$ to a QCD NLO calculation can be seen in Figure 1.

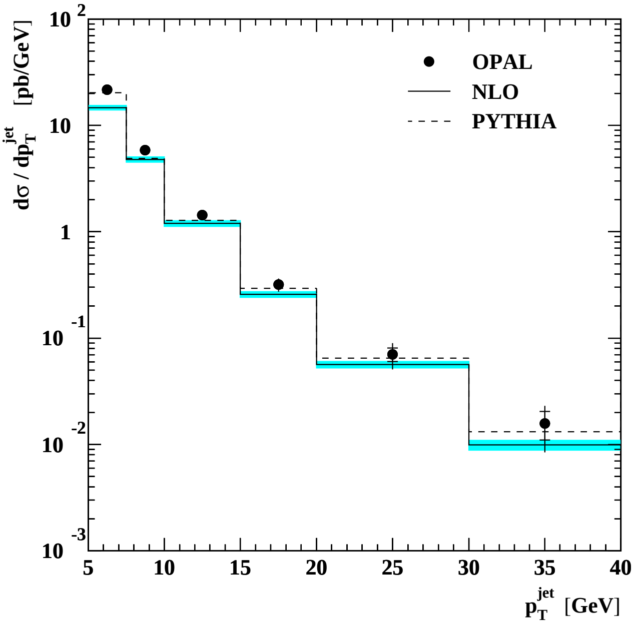

Figure 1: Inclusive jet production differential cross section, $\mathrm{d}\sigma/\mathrm{d}p_{\mathrm{T}}^{\mathrm{jet}}$ for all jets with $|\eta_{\mathrm{jet}}| < 1.5$ compared to NLO and PYTHIA 6.221 Monte Carlo predictions.

3. **I evaluated the number of fake Level-1 di-muon triggers with the ATLAS detector coming from the overlaps of the muon detector chambers. Using the optimal configuration I calculated the expected fake Level-1 di-muon trigger rates at ATLAS and verified on B-physics samples that the configuration does not degrade the physics performance of the detector. [3, 5–7]**

Selecting B-physics events at the LHC is a non-trivial task. These events usually do not produce leptons or jets with high transverse momenta, or an overall large energy deposit in the detector. Because of the design of the Level-1 trigger, one can not use complicated signatures for selecting these events, which makes triggering on certain kinds of B-physics events at high luminosities of the LHC impossible. However, channels that produce two low-p_T muons in their final state will be possible to select efficiently with an acceptable rate even at the highest designed luminosity (10^{34} cm^{-2}s^{-1}).

In order to maximise the acceptance of the detector for muons, there are many places where the muon trigger chambers overlap with each other. Because of the design of the Level-1 muon trigger, a single muon can be detected as multiple muon candidates if it traverses such an overlap region of the detector. There are multiple ways of handling the fake di-muon trigger signals arising from this. It was my responsibility to create the configuration of the Muon to CTP Interface (MuCTPI) part of the ATLAS Level-1 muon trigger for suppressing the fake di-muon trigger signals.

To create the optimal configuration, I had to analyse large numbers of so called single-muon events – events which simulate a single muon escaping the detector, simulating the full detector response. Calculating the expected rate of fake di-muon triggers without and with the usage of the MuCTPI to suppress the fake double-counts, I showed that the rate of such events can be lowered by about 70%. The rest of the fake di-muon triggers can then be handled in the High Level Trigger.

It is important to check the effects of the trigger selection on our ability to measure various quantities. I studied the effects of the overlap handling in the Level-1 muon trigger on selecting $B_s \rightarrow \mu^+\mu^-\Phi$ and $B^+ \rightarrow J/\psi(\mu^+\mu^-)K^+$ decays. My studies have shown that the overlap handing has no undesirable effect on the selection of such events and that biases coming from the Level-1 muon trigger can be corrected for in various physics distributions.

4. **I calculated the expected efficiency of the muon trigger chains in the ATLAS experiment to select events containing the decay of a top quark pair ($t\bar{t}$). I have found that the single-muon trigger of ATLAS is capable of selecting $t\bar{t}$ events with high efficiency at an acceptable total trigger rate. [7]**

The LHC will provide its experiments with an unprecedented number of $t\bar{t}$ pairs. Understanding the various trigger efficiencies for selecting these events will be very important from the start of the LHC data-taking to enable precise cross section measurements.

It is possible to use the single-lepton triggers of ATLAS to efficiently select semi-leptonic $t\bar{t}$ decays – decays where one of the W-s produced in the top quark decay decays to a lepton and a neutrino – because of the hard p_T spectrum of the leptons in these decays. The efficiency of all three trigger levels of ATLAS can be described by measuring the efficiency of the trigger to select a simulated or reconstructed muon which has certain properties.

Finally, I demonstrated on an artificially mixed Monte Carlo sample how to use the trigger efficiency measurements in a simple top quark pair creation cross section analysis.

Using the efficiencies that I calculated for the various trigger configurations, I demonstrated in a simplified $t\bar{t}$ reconstruction and cross section calculation analysis how the trigger efficiency can be folded into the calculation of the $\sigma_{t\bar{t}}$ production cross section. Figure 2 shows the mass distribution of the hadronically decaying top quarks reconstructed by my analysis for regular Monte Carlo-s and a special Monte Carlo mixture called *streamtest data*.

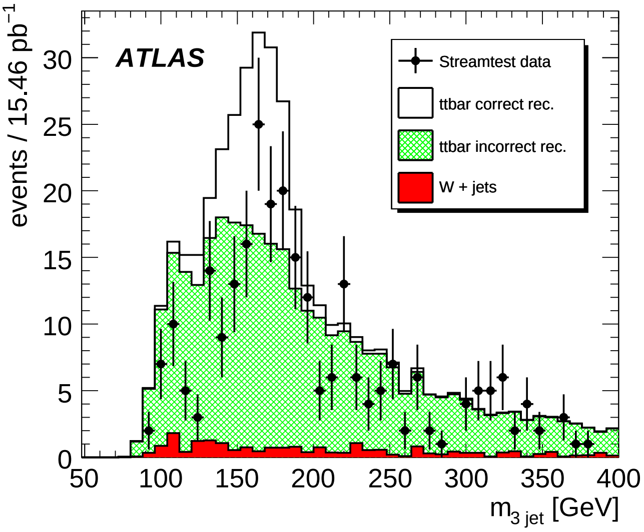

Figure 2: Reconstructed top quark mass distribution comparing streamtest data with $t\bar{t}$ and W + jets Monte Carlo.

Publications in peer reviewed journals related to the thesis

[1] G. Abbiendi *et al.* [OPAL Collaboration, 208 authors including A. Krasznahorkay], *"Inclusive Jet Production in Photon-Photon Collisions at $\sqrt{s_{ee}}$ from 189 to 209 GeV"*,
Phys. Lett. B **658** (2008) 185–192

[2] G. Aad *et al.* [ATLAS Collaboration, 2926 authors including A. Krasznahorkay], *"The ATLAS Experiment at the CERN Large Hadron Collider"*,
Journal of Instrumentation (JINST) **3** S08003 (2008),
`http://dx.doi.org/10.1088/1748-0221/3/08/S08003`

[3] S. Ask *et al.* (22 authors including A. Krasznahorkay), *"The ATLAS central level-1 trigger logic and TTC system"*,
Journal of Instrumentation (JINST) **3** P08002 (2008),
`http://dx.doi.org/10.1088/1748-0221/3/08/P08002`

Other publications related to the thesis

[4] A. Krasznahorkay *for the OPAL Collaboration*, *"High momentum hadron and jet production in photon-photon collisions at LEP2"*, Proc. of the 15th Int. Workshop on Deep-Inelastic Scattering and Related Subjects, Munich, April 2007, `http://dx.doi.org/10.3360/dis.2007.173`

[5] A. Krasznahorkay *for the ATLAS and CMS Collaborations*, *"Outlook for b physics at the LHC in ATLAS and CMS"*, Proc. of the 15th Int. Workshop on Deep-Inelastic Scattering and Related Subjects, Munich, April 2007,
`http://dx.doi.org/10.3360/dis.2007.167`

[6] S. Haas *et al.* (10 authors including A. Krasznahorkay), *"The octant module of the ATLAS level-1 muon to central trigger processor interface"*, Proc. of the 12th Workshop on Electronics for LHC and Future Experiments (LECC 2006), Valencia, Spain, 25-29 Sep 2006, pp.319–322

[7] The ATLAS Collaboration (2926 authors including A. Krasznahorkay), *"Expected Performance of the ATLAS Experiment, Detector, Trigger and Physics"*, CERN-OPEN-2008-020, Geneva (2008), to appear

I am also a co-author of more than 40 other scientific publications.