Measurement of Double Differential $t\bar{t}$ Production Cross Sections with the CMS Detector

Dissertation
zur Erlangung des Doktorgrades
des Fachbereichs Physik
der Universität Hamburg

vorgelegt von

Ievgen Korol

aus Ukrainka (Ukraine)

Hamburg

2015

Gutachter der Dissertation:

Gutachter der Disputation:

Datum der Disputation:

Vorsitzender des Prüfungsausschusses:

Vorsitzender des Promotionsausschusses:

Dekan der MIN Fakultät:

Abstract

Kurzfassung

Contents

Chapter 1

Introduction

Nowadays the heaviest known elementary elementary particle is the top quark. Having a much smaller size then a proton, it is as heavy as the atom of gold. The search for the heaviest particle lasted more then two decades and successfully ended in March 1995 at Fermi National Accelerator Laboratory, Fermilab, where the discovery of the top quark was announced [!!!].

The third generation of quarks, which included top and bottom quarks, was predicted in 1973 by Kobayashi and Maskawa [!!!]. But a huge mass of a top quark was not expected, so it couldn't be discovered so long. While it's partner, the bottom quark, was experimentally found already in four years after the theoretical prediction.

Thus, to produce a top quark one needs to concentrate immense amount of energy into a small region of space. This is done on the accelerator experiments. And the most powerful accelerator nowadays is the Large Hadron Collider (LHC), CERN. Delivering proton-proton collisions which had the center of mass energy of 8 TeV in 2012, it became a real top quark factory. The large number of the events with top quark, which were produced on the LHC, gives us a unique possibility to study precisely the properties of the heaviest quark.

The top quarks are dominantly produced in pairs, decaying before they could hadronize. Each top quark of the pair decays to a W boson and a b quark. And a W boson has several decay channels. In this work only the channel where W bosons from top quarks decay to two leptons is studied. For this purpose the $19 fb^{-1}$ data sample with 8 TeV center-of-mass energy taken in 2012 is used.

This work represents the first measurement of the normalized double differential top pair production cross section at the LHC. This measurement is done in totally XXX diffferent variables connected to the top kinematics. The comparison to the theory predictions is also performed.

In order to contribute to the future measurements with the higher statistics during the next years runs of the LHC, a part of my work was connected to the studies of irradiated prototype silicon sensors and readout chips for the Phase-I upgrade of the CMS pixel detector.

This work is structured the following way.

Chapter 2

The Standard Model of Particle Physics

This chapter is an introduction to the Elementary Particle Physics in the view of Standard Model. First the particles are described, then the way they interract is shown. The short introduction to the top physics is given in the end.

2.1 Introduction. Elementary Particle physics

The main question which the elementary particle physics addresses is '*What is the matter made of?*' This question was stated many thouthands years ago and is still of current interest. First guesses about the structure of matter were made already in ancient Greece by a phylosopher-atomist Demokrit, who claimed that everything around us consists of tiny undevidable chuncs called *atomos* [1]. But the elementary particle physics (elementary here means unstructured) in modern sense started with J.J. Thomson's discovery of *electron* [2] in 1897. The electrons were correctly surmised to be constituents of atoms. The full picture of the atom structure was created after Ernest Rutherford's scattering experiment [3], thus proving atom to be non-elementary particle. It actually consists of a heavy positively charged core, called *nucleus* and very light negatively charged electrons, moving around like satelites. The nucleus was also proven to be non-elementary. But no structure of electron was discovered and it is nowadays known as one of the undevidable particles.

Many other elementary particles were subsequently discovered the last sixty years. Now having an idea what are the structureless bricks making up matter in the Universe, particle physycs states another important question: '*How do the particles interact?*'.

The Standard Model of particle physics is a theory which is summing up the constituents of the Universe and interactions between them. This theory is overall successfully describing many phenomena and agrees with the experimental efforts. But there is also a number of challenges which Standard Model is facing. In particular

- the gravitation is not described,
- the neutrino oscillations and their non-zero masses are not explained,
- dark matter and dark energy do not fit into the model,
- the matter-antimatter asymmetry in the Universe is not explained.

2.2 Elementary Particles

This chapter is the answer which the Standard Model gives to the question '*What is the matter made of?*'. The Standard Model asserts that all the material in the Universe is made up of the elementary *fermions* (particles which have half-integer spin – $\frac{n}{2}\hbar$, $n = 1, 2, 3, ...$) interacting through the fields, carried by *bosons* (particles which have integer spin – $n\hbar$, $n = 0, 1, 2, 3, ...$). The names of the particles originate from the statistics they obay. Fermions follow the Fermi-Dirac statistics, bosons – Bose-Einstein statistics. Another thing which is different for the fermions and bosons is how their wave functions behave. After swapping two bosons in a system, the wave function does not change, it is symmetric to the exchange of bosons. While the wave function of fermions changes the sign, it is asymmetric.

The Fig.2.1 shows all the elementary constituents of matter and fields.

2.2.1 Leptons

The two bottom rows of fermions at the Fig.2.1 represent the known *leptons* with their masses, charges and spins.

In general, the fermions are described with the Dirac equation [4]:

$$i\hbar\gamma^\mu\partial_\mu\psi - mc\psi = 0, \tag{2.1}$$

where the ψ is a four-element Dirac spinor, an equivalent of a one dimentional Schrödinger wave function, γ^μs are the gamma matricies and ∂_μ is a partial derivative with respect to the time-space four-vector components.

Dirac equation 2.1 has solutions with positive but also with negative energy states. Those are treated as *antiparticles*. So every lepton, being a fermion, has an antiparticle. At the Fig.2.1 only particles are shown. Electron e^- has an antiparticle positron e^+. The muon μ^-, tau τ^- and their antiparticles, μ^+ and τ^+ differ from the electron and positron only by their masses and their lifetimes.

Neutral leptons, neutrinos ν, also have antiparticles, antineutrinos $\bar{\nu}$. Every massive lepton has a corresponding neutrino: ν_e, ν_μ and ν_τ. It is believed that in the interactions

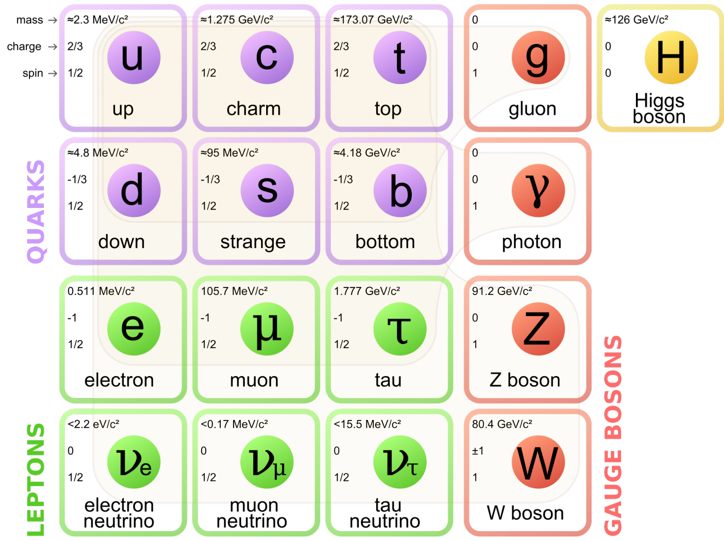

Figure 2.1: The Standard Model of Elementary Particle Physics with three generations of matter fermions, field bosons and a Higgs boson. The properties of the particles are also shown in each box.

a lepton can change only to another of this type. This is known as *conservation of lepton number*. In this rule leptons have positive lepton numbers and antileptons – negative ones.

2.2.2 Quarks

The upper two rows

Chapter 3

Experimental Setup

Every theory needs experimental proof. Particle physics is tested on colliders.

The Standard Model was experimentaly tested up to scale of TeV, Needed to go higher to study electroweak symmetry breaking and Higgs mechanism.

Physics beyond SM is also of interest on the scales >1TeV.

Previous colliders - designed up to 1 TeV. LHC [5] was working with the energy up to 8 TeV - eightfold increase of energy, many physics perspectives.

One of the general purpose detectors on the LHC is CMS.

This chapter - 2 parts. About LHC and CMS

3.1 Large Hadron Collider

The LHC is the largest experimental facility ever built, at European Organization for Nuclear research, CERN.

LHC - two ring superconductiong proton-proton (or lead nuclei) collider.

The circumference of the ring is 26.7 km which was former used for the LEP experiment.

It lays under the surfaces of Switzerland and France on the depth 50 to 170 m.

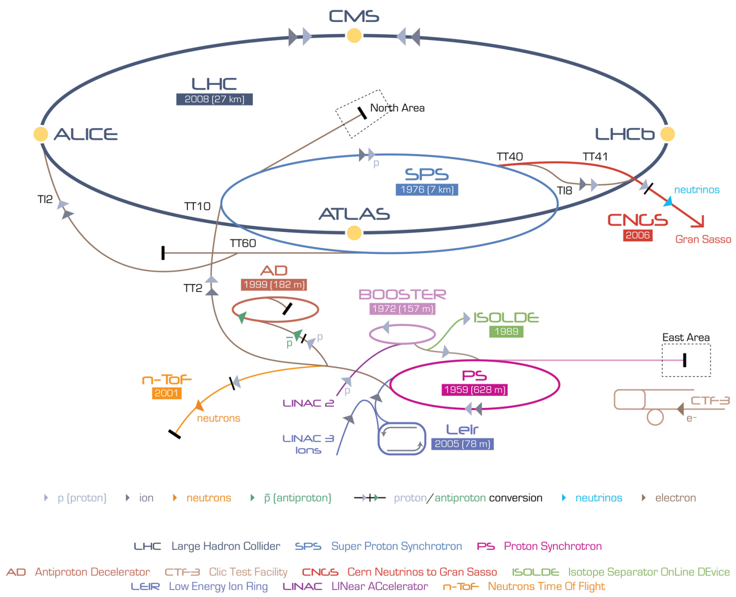

Figure 3.1: The complex of accelerators at CERN with their length and particles being accelerated inside.

——Designed center-of-mass energy for proton beams – 14 TeV. It is reached in several steps in preaccelerator system of LHC and afterwards injected to the largest ring.

The whole accelerator system is on Fig.3.1.

Each accelerator in the chain boosts the energy of the particles beams and injects them to the next machine in the preaccelerator chain. The LHC is the last accelerator in the sequence.

The first accelerator on the way to the LHC is the Linac2. It injects protons or heavy ions to the Proton Synchrotron Booster (PSB). Then the particle beams arrive to Proton Synchrotron (PS) followe by Super Proton Synchrotron (SPS).

And finaly the beams are transfered to the two pipes of the LHC. Beams inside one of the pipes circulate clockwise and in the other – anticklockwise.

The whole preaccelerations takes four and a half minutes, while the particles in the LHC circulate 20 minutes to reach the final energy.

——The designed working centre-of-mass energy at the LHC is $\sqrt{s} = 14TeV$, but from the safety point of view it first operated at the smaller energies – $\sqrt{s} = 7TeV$ and $\sqrt{s} = 8TeV$

up to the end of 2011 and 2012 correspondingly.

And after a long shutdown and a sequence of the upgrade workarounds the machine is ready for the operation with the centre-of-mass energies of $\sqrt{s} = 13TeV$ and finally $\sqrt{s} = 14TeV$.

——Another parameter of the LHC which is very important for the experimental results is the *luminosity*, L.

It desribes the rate of events $\frac{dN}{dt}$, taking their cross section σ into account:

$$L\sigma = \frac{dN}{dt}. \tag{3.1}$$

Equation3.1 shows that the measurement of the cross section of any process needs the luminosity value, which is an accelerator parameter and is given as [6]:

$$L = \frac{\gamma f k_B N_p^2}{4\pi\epsilon_n\beta}F, \tag{3.2}$$

where γ is a relativistic gamma factor, f is a revolution frequency, k_B is a number of bunches, N_p is a number of particles per bunch, ϵ_n is a normalized transverse emittance (designed value is $3.75\mu m$), β is the focus of the beam and F is a reduction factor due to the crossing angle at the interaction point.

The designed luminosity is $L = 10^{34}cm^{-2}s^{-1}$ which leads to arround 1 billion proton-proton interactions per second.

——There are other accelerator parameters which are relevant for the physics analysis. Some of them were mentioned above.

Bunches of protons are formed in the PS with the time spacing of 25 ns. The number of proton bunches in the LHC is 2808. Each bunch has 11

——There are four points on the LHC ring where the two beams can coincide. The detectors are located there.

The four experiments on the LHC machine are *ATLAS*, *CMS*, *ALICE* and *LHCb*.

Bibliography

[1] C. Yang, "Elementary particles," *Princeton University Press*, 1961.

[2] J. Thomson, "Cathode Rays," *The Electrician*, vol. 39, p. 104, 1897.

[3] E. Rutherford, "The Scattering of α and β Particles by Matter and the Structure of the Atom," *Phil. Mag.*, vol. 21, pp. 669–688, 1911.

[4] P. A. M. Dirac, *Principles of Quantum Mechanics (4th ed.).* Clarendon, 1958 (reprinted 2011).

[5] L. Evans, P. Bryant, *et al.*, "LHC Machine," *JINST*, vol. 3, 1911.

[6] G. Bayatian *et al.*, "CMS physics: Technical design report," 2006.