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

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**vorgelegt von**

**Ievgen Korol**

**aus Ukrainka (Ukraine)**


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# 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 $\psi$ is a four-element Dirac spinor, an equivalent of a one dimentional Schrödinger wave function, $\gamma^{\mu}$s are the gamma matricies and $\partial_{\mu}$ 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 $\mu^-$, tau $\tau^-$ and their antiparticles, $\mu^+$ and $\tau^+$ differ from the electron and positron only by their masses and their lifetimes.

Neutral leptons, neutrinos $\nu$, also have antiparticles, antineutrinos $\bar{\nu}$. Every massive lepton has a corresponding neutrino: $\nu_e$, $\nu_\mu$ and $\nu_\tau$. It is believed that in the interactions

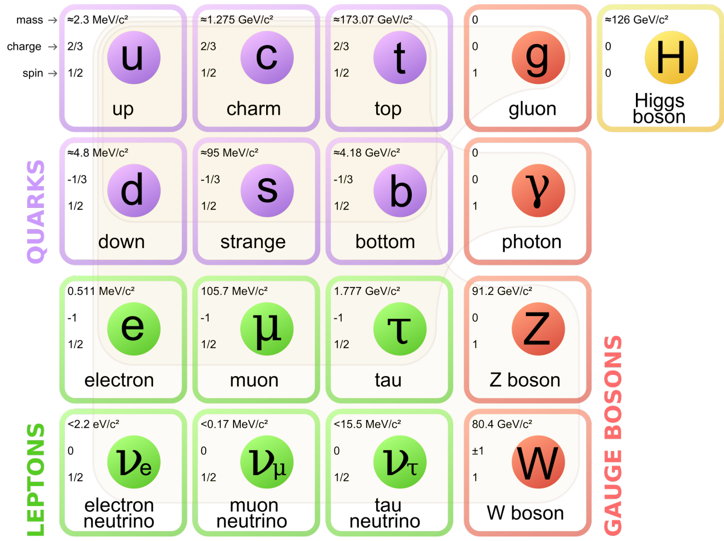


Figure 2.1: The Standard Model of Elementary Particle Physics with three generations of matter fermions, field bosons and a Higgs boson. The properties of the particles are also shown in each box.

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 fastest protons in the world, ever controlled by human , are alive in Switzerland at CERN. The Machine which can manage the operation of these protons is called Large Hadron Collider(LHC). The LHC is a ring-shape tunnel 26.7 km long placed 45 -170 meter ungrounded. Inside the tunnel there are two rings with vacuum tubes where proton(or lead nuclei) beams are circulating in different directions. There are four locations where tings are crossing and the protons can collide with each other. The designed center-of-mass energy for those collisions is $\sqrt{s} = 14$ TeV, which means 7 TeV in one direction.

Not to get out of the ring 7 TeV protons are guided by 8 T supperconducting magnets. For optimal useg of these magnets one neds to preaccelerate and preforme the proton

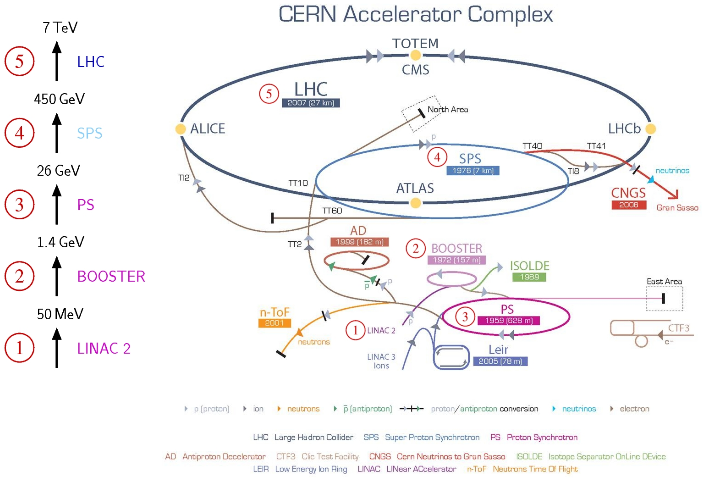


Figure 3.1: The complex of accelerators at CERN with their length and particles being accelerated inside.

banches. For this porpose LHC is supported by preacceleration system shown at Fig. 3.1

The way of the protons literaly starts fron a bottel of hydrogen gass.

[http://www.lhc-closer.es/1/3/10/0]

To kep running LHC during the 2012 data taking periud was used only 1 cubic suntemiter of H2 gass.

The whole accelerator system is on Fig.3.1.

The measurements of collision products are done with the complex particle detectors. There are four of them on the LHC ring, each located around the point where beams of particles of different directions are brought together. These detectors have different construction thus having slightly different goals. The four experiments based on the corresponding LHC detectors are called *ALICE*, *LHCb*, *ATLAS* and *CMS*.

- The ALICE (A Large Ion Collider Experiment) [6] is a detector experiment on the LHC which is designed to work with the heavy ion collisions. LHC can also perform as a heavy ion accelerator. The last run was providing the lead on lead collisions at $\sqrt{s_{NN}} = 2.76$ . The goal of the ALICE experiment studies is the strongly interacting matter in extremely high density state called *quark-gluon plasma*. This state of matter provides a unique possibility to find a bare quark without a pair and also to study the early Universe which was so dense at the first moments after the Big Bang.
  The ALICE detector weights 10000 tonnes and is 26 m long, 16 m high and 16 m wide. It sits on the depth of 56 m below the ground.

- The LHCb (Large Hadron Collider beaty) [7] is investigating the $CP$ violation and hevy flavour physics via the rare $B$ hadron decays. As the $b\bar{b}$ pairs are mostly produced in the forward and backward directions, and their production cross section is very high there was no need to construct a big and expensive $4\pi$ detector complex. For this reason the LHCb is a one side spectrometer corresponding to the forward beam direction. For a better detection of the $b$-decays the LHCb features a movable tracking system which can go very close to the beampipe.

The LHCb detector weights 5600 tonnes and is 21 m long, 10 m high and 13 m wide. It sits on the depth of 100 m below the ground.

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