Top quark physics at the LHC with the CMS detector

Sergey Senkin

School of Physics

University of Bristol

A dissertation submitted to the University of Bristol in accordance with the requirements of the degree of Doctor of Philosophy in the Faculty of Science

Autumn 2013

Declaration

I declare that the work in this dissertation was carried out in accordance with the Regulations of the University of Bristol. The work is original except where indicated by special reference in the text and no part of the dissertation has been submitted for any other degree. Any views expressed in the dissertation are those of the author and in no way represent those of the University of Bristol. The dissertation has not been presented to any other University for examination either in the United Kingdom or overseas.

Signed:........................ Date:........................

Contents

1. Introduction

Not really sure what to write here

2. Theoretical background

2.1 Standard Model

Yet to be written...

3. The LHC and the CMS detector

3.1 The Large Hadron Collider

The LHC [1] is currently the largest and the most powerful particle accelerator ever built. It is installed in the 26.7 km tunnel that was originally constructed for the LEP accelerator in the 1980s. The tunnel lies at a depth of 45 m to 170 m underground between the Jura mountain and the Lake Geneva, being the main part of the CERN accelerator complex.

The machine is designed to accelerate proton beams and provide collisions at a centre of mass energy of $\sqrt{s} = 14$ TeV. Unlike particle-antiparticle colliders, the LHC requires two rings with opposite magnetic dipole fields in order to maintain and collide two counter-rotating proton beams. Since the tunnel was originally designed for the electron-positron LEP, it has an internal diameter of 3.7 m which is not enough to install two separate independent rings. Therefore, a twin-bore magnet design was adopted [2], which also came as a substantial cost-saving measure.

A schematic view of the LHC accelerator chain is shown on Fig. 3.1. In the beginning, the protons are obtained by stripping orbiting electrons from hydrogen atoms. Then they are injected into the linear accelerator LINAC2 to reach the energy of 50 MeV and enter the Proton Synchrotron Booster (PSB). The booster accelerates them to 1.4 GeV and passes the beam to the Proton Synchrotron (PS) where the energy rises to 25 GeV. In the next step, protons enter the Super Proton Synchrotron (SPS) where they are accelerated to 450 GeV. Finally, the

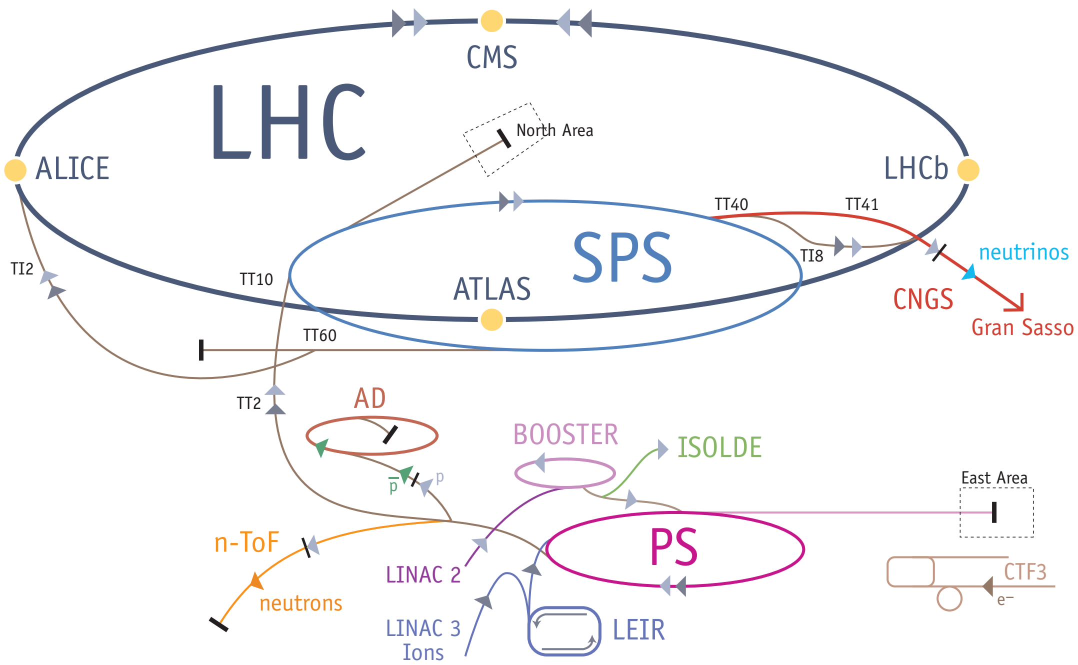

Figure 3.1: CERN accelerator complex.

beam is transferred to the LHC in both clockwise and anti-clockwise directions where it takes about 20 minutes to reach the design 7 TeV energy (per beam).

[add the number of magnets, total energy stored, number of bunches, bunch spacing etc.?]

The LHC has four interaction points, providing collisions to four major experiments. Two of them, CMS and ATLAS, are multi-purpose high-luminosity experiments with a peak luminosity of $L = 10^{34}$ cm^{-2} s^{-1}. The other two experiments operate at low luminosities and have more specific physics goals: LHCb studies b-meson decays, and Alice is a dedicated heavy ion experiment.

The instantaneous luminosity of a collider can be calculated as

$$L = \frac{n_1 n_2 f}{4\pi\sigma_x\sigma_y}, \tag{3.1}$$

where n_1 and n_2 are the numbers of particles in each of the colliding bunches, f is the revolution frequency, σ_x and σ_y are the horizontal and vertical beam sizes, assuming the two beams have the same size.

The number of events generated in the collisions per second is given by

$$N_{events} = L \times \sigma, \tag{3.2}$$

where σ is the cross section of the process under study.

[add the plots with cross sections and production rates?]

The LHC started operating on the 10th of September 2008, with the first beams fully circulating in both rings. However, only 9 days later a magnet quench occurred in two sectors of the tunnel, which was caused by an electrical fault due to a bad connection between two magnets. A consequent liquid helium explosion damaged a total of 53 superconducting magnets. Over a year was spent on repairs and tests, and the first collisions were recorded on the 23rd of November 2009 at a centre of mass energy of 0.9 TeV. The following few months showed the continuous ramp up of the beam energies up to 3.5 TeV per beam which was achieved on the 30rd of March 2010 when the LHC physics program started.

Throughout the rest of the 2010 major LHC experiments (CMS and ATLAS) recorded approximately 40 pb^{-1} of data, which resulted in the first measurements of various physics processes at the LHC. The following year became the main 7 TeV data-taking period, with about 5 fb^{-1} of data recorded by ATLAS and CMS. On the 5th of April 2012 the centre of mass energy was increased to 8 TeV, and July of 2012 marked the first major discovery of a new boson which was later shown to be consistent with the Standard Model Higgs boson, according to approximately 21.8 fb^{-1} of data recorded until early 2013. A long shut-down is planned for the following two years with various upgrades scheduled. The next physics run is expected in 2015 with the beam energy increased up to 6 or 7 TeV.

[add any upgrade details and distant future plans, like SLHC?]

3.2 The CMS Detector

The Compact Muon Solenoid [3] is a general-purpose detector designed to carry out precise measurements of the Standard Model and the searches for physics beyond it. The primary design requirement was the ability to discover the nature of electroweak symmetry breaking, and the first observation of a Higgs boson was obtained in the Summer of 2012 [4].

The detector is installed at one of the LHC interaction points (Point 5) at about 100 m undeground near the French village of Cessy, between the Jura mountains and Lake Geneva. The overall dimensions of the CMS detector are a length of 21.6 m, a diameter of 14.6 m and a total weight of 12500 tons.

The sectional view of CMS is shown on Fig. 3.2. In the centre of the detector, tracking and calorimetry systems are surrounded by the superconducting solenoid. On the outermost part of it the magnetic flux is returned through the iron yoke in which the muon system is also integrated. All the sub-systems are discussed in the following sections with more detail.

The cylindrical shape of the CMS detector dictates using the cylindrical coordinate system, with the origin centered at the interaction point, the x-axis pointing towards the centre of the LHC ring, the y-axis pointing upwards and the z-axis pointing along the beamline in the anti-clockwise direction. The azimuthal angle ϕ is measured from the x-axis in the transverse $(x - y)$ plane and

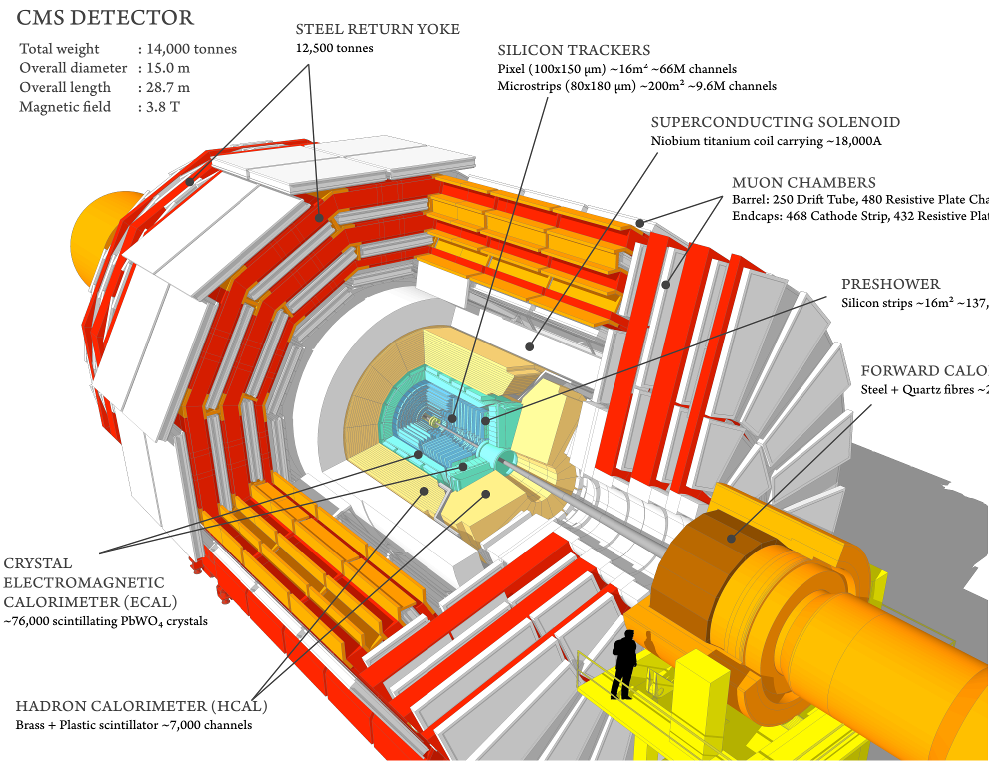

Figure 3.2: Sectional view of the CMS detector.

the polar angle θ is measured from the z-axis. Tha radial distance to the beamline is denoted as r. Pseudorapidity is defined as:

$$\eta = -\ln\tan\frac{\theta}{2}. \tag{3.3}$$

This implies that the particles moving in the transverse plane (perpendicular to the beamline) have a pseudorapidity of 0, whereas the beam direction has an infinite pseudorapidity. Considering the cylindrical shape of the detector, it has the barrel and the endcaps regions, with the transition occuring at $\eta = 1.4$. The momentum and energy transverse to the beamline are denoted by p_T and E_T respectively; the imbalance of the energy measured in the transverse plane, called missing transverse energy, is denoted by $E_{\mathrm{T}}^{\mathrm{miss}}$.

3.2.1 Inner Tracking System

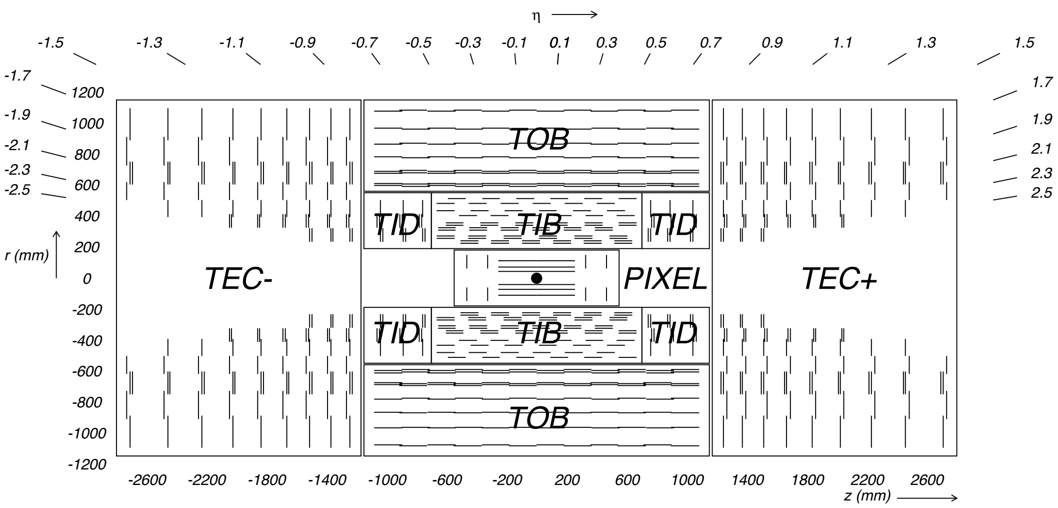

Figure 3.3: Sectional view of the tracker system.

3.2.2 Electromagnetic Calorimeter

3.2.3 Hadron Calorimeter

3.2.4 Superconducting Magnet

3.2.5 Muon System

3.2.6 Trigger and Data Acquisition

[1.4 experimental challenge in TDR]

3.3 Computing

3.4 Object Reconstruction

3.4.1 Electron Reconstruction

3.4.2 Muon Reconstruction

3.4.3 Jet Reconstruction

3.4.4 Missing Transverse Energy

3.5 Summary

4. High level trigger development for Top Physics

5. Top Quark mass measurement

6. Differential cross section measurement

Measurement of the differential cross section of the top quark pairs with respect to different variables is an important precision measurement, but it can also give hints of new physics. For example, measurement of the missing energy in $t\bar{t}$ events can represent a search for invisible particles produced in association with top quarks.

6.1 Data and Simulation

6.2 Event Selection

6.3 Choice of binning

6.4 Differential cross section measurement

6.5 Unfolding

6.6 Systematic Uncertainties

6.7 Results

7. Conclusions

References

[1] L. Evans and P. Bryant. LHC Machine. *JINST*, 3(08):S08001, 2008. 3

[2] J.P. Blewett. 200 GeV intersecting storage accelerators. In *Proceedings of The 8th International Conference on High-Energy Accelerators*, page 501, Geneva, Switzerland, 1971. CERN. 3

[3] The CMS Collaboration. The CMS experiment at the CERN LHC. *JINST*, 3(08):S08004, Aug 2008. 6

[4] The CMS Collaboration. Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC. *Physics Letters B*, 716(1):30 – 61, 2012. 6